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Title: Water Imaging in Mirai Short-Stack provided by USCAR

Author(s): Borup, Rodney L.

Intended for: Presentation to USCAR (GM and Ford) plus distribution to other automotive OEMs, Honda, Toyota, Bosch

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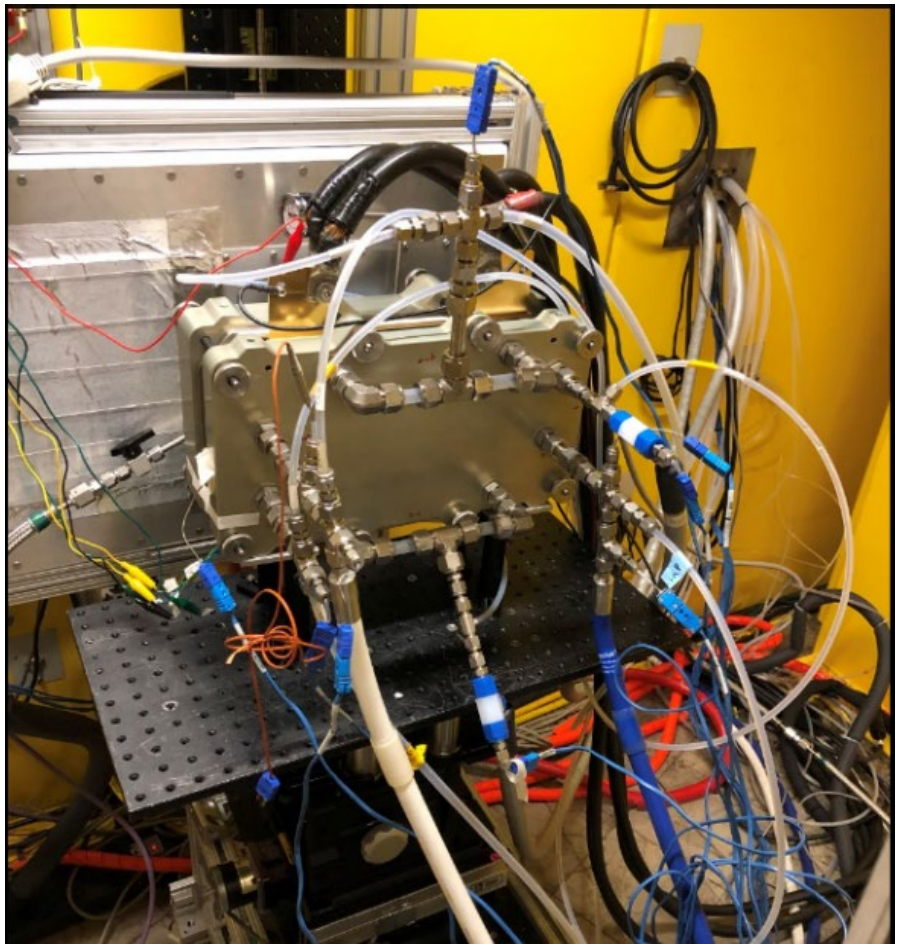
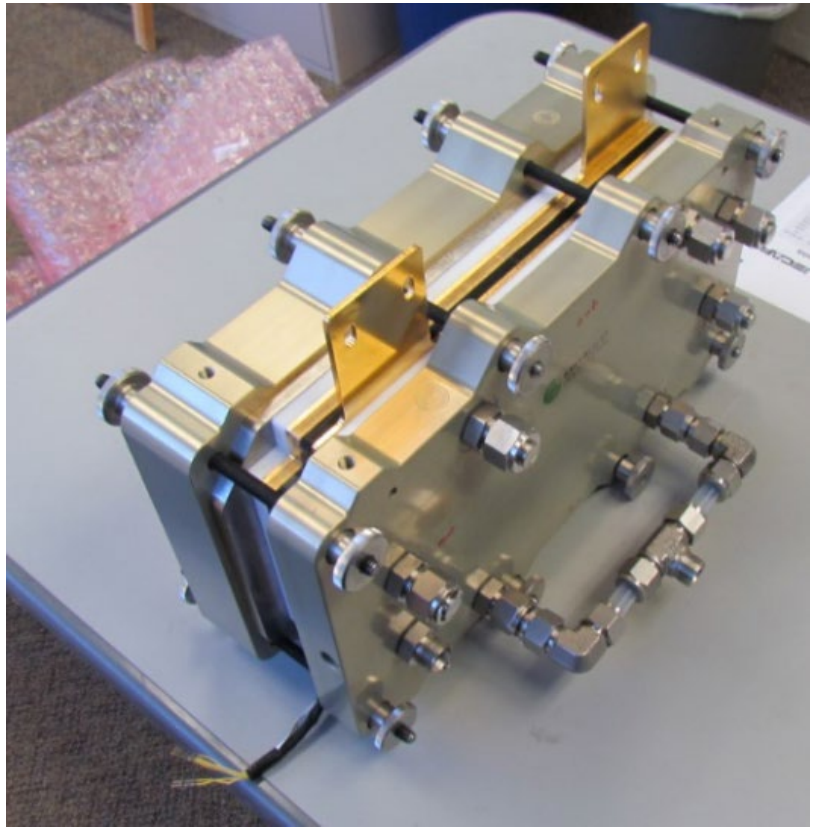
Water Imaging in Mirai Short-Stack provided by USCAR

LANL: Kavi Chintam, Derek Richard, Andrew Baker, Rod Borup

NIST: Jake LaManna, Dan Hussey, Eli Baltic, David Jacobson

USCAR: Dave Masten, Joe Fairweather, Sinichi Hirano, Chunchuan Xu





Mirai Component Summary

Cathode

- ~ 0.33 mg_{Pt}/cm^2 -- Cathode layer ~ 9 μm
  - Cathode Layer decreases in thickness to about 8.1 mm at 3000 hrs
- PtCo/C: Pt/Co=6.6, Pt = 87mole%, Co = 13mole% (XRF)

Anode

- 0.05 mg_{Pt}/cm^2 -- Anode layer ~ 2.3 μm

Total Mirai Stack Loading: ~ 26 g Pt (255 cm^2 active area * 0.38 mg Pt/cm^2 * 270 cells)

Membrane

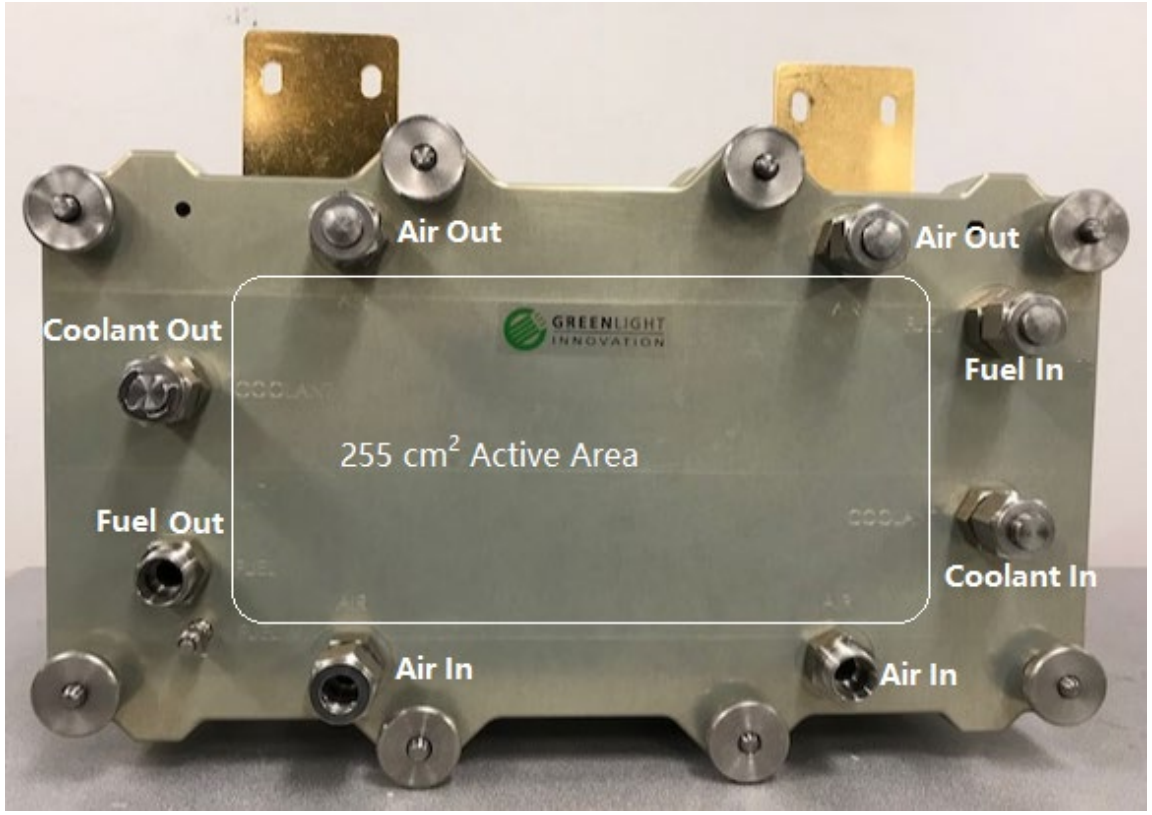
- ~10 – 10.5 μm with ePTFE
- Ce = ~ 1 - 2.5μg/cm^2 -- large amounts of Ce in GDL MPLs

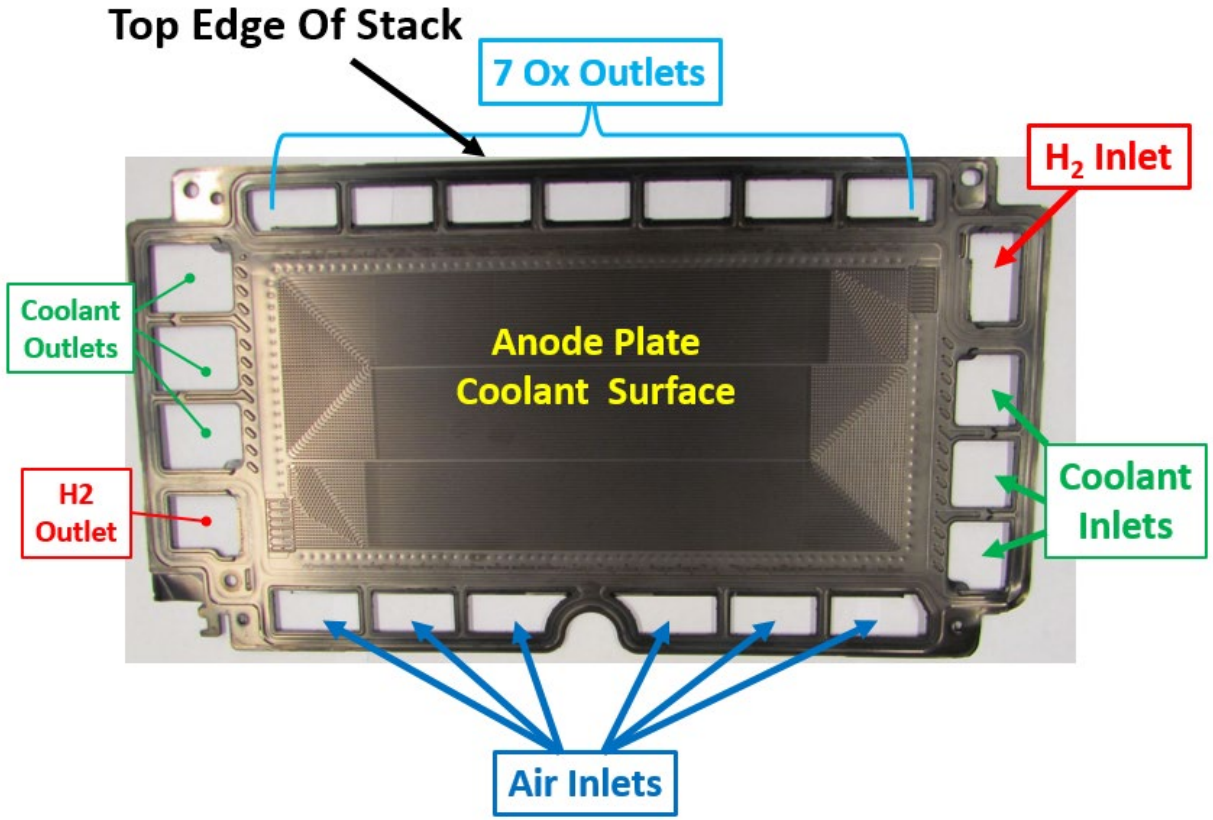
GDLs

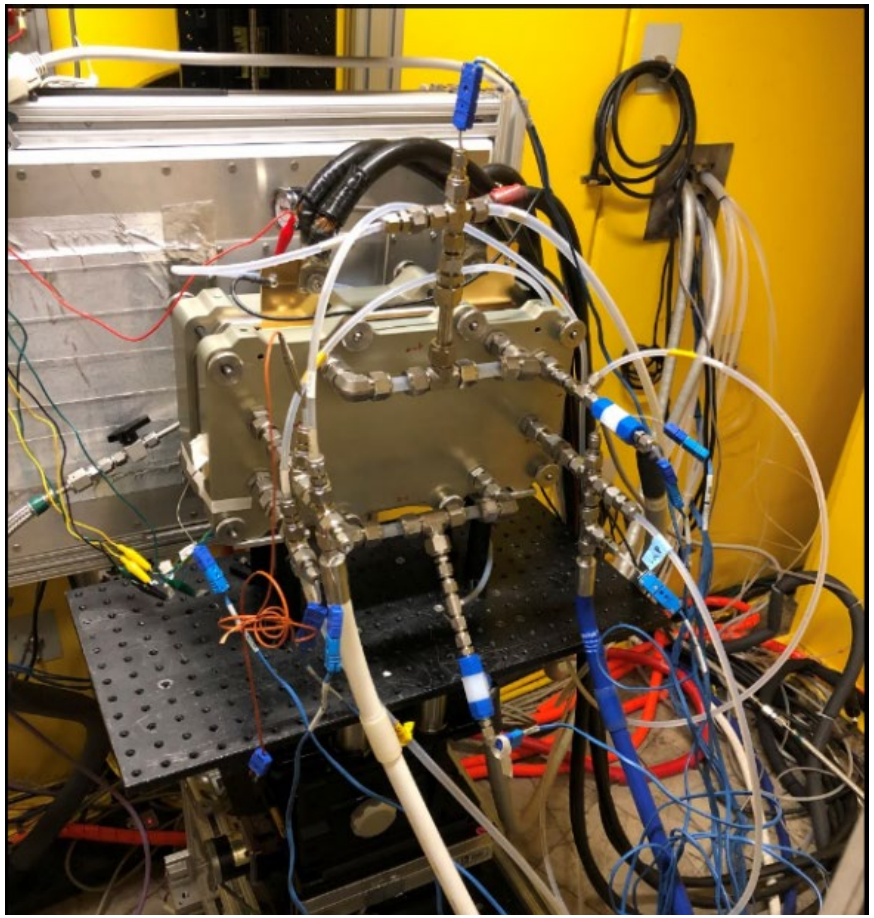
- PAN Fiber Substrate with MPL
- Anode: ~ 150 μm total with about 60 μm MPL
- Cathode: ~ 160 μm total with about 40 μm MPL

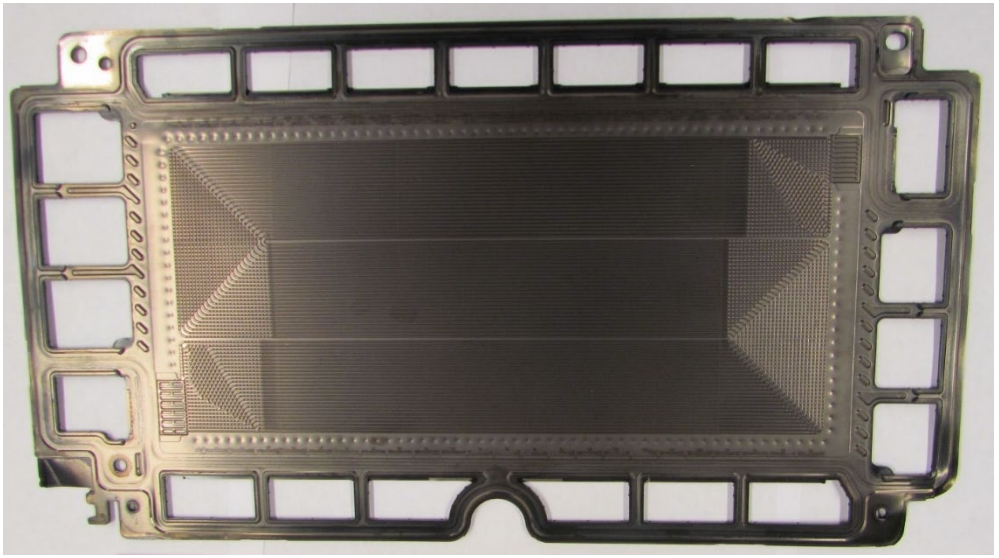
Toyota Mirai 5 Cell Short-Stack Dimensions/ Materials

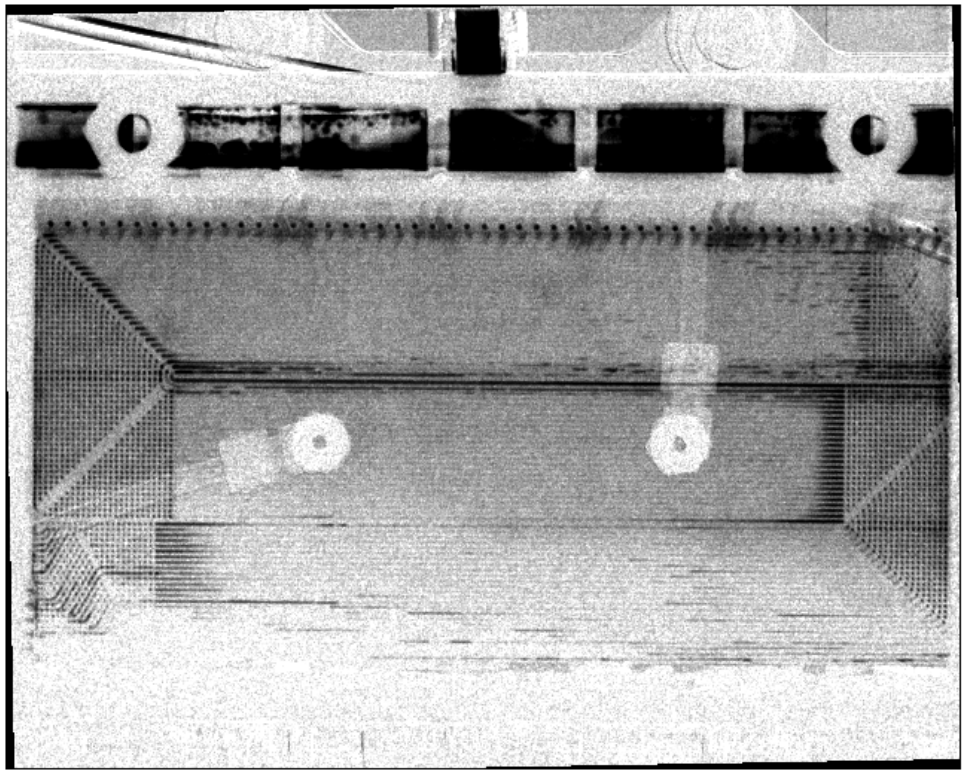
- 5 cell- 255 cm^2 active area per cell, the plate materials and Dimension/thickness labeled in picture.











Approximate Toyota Mirai Operating Conditions

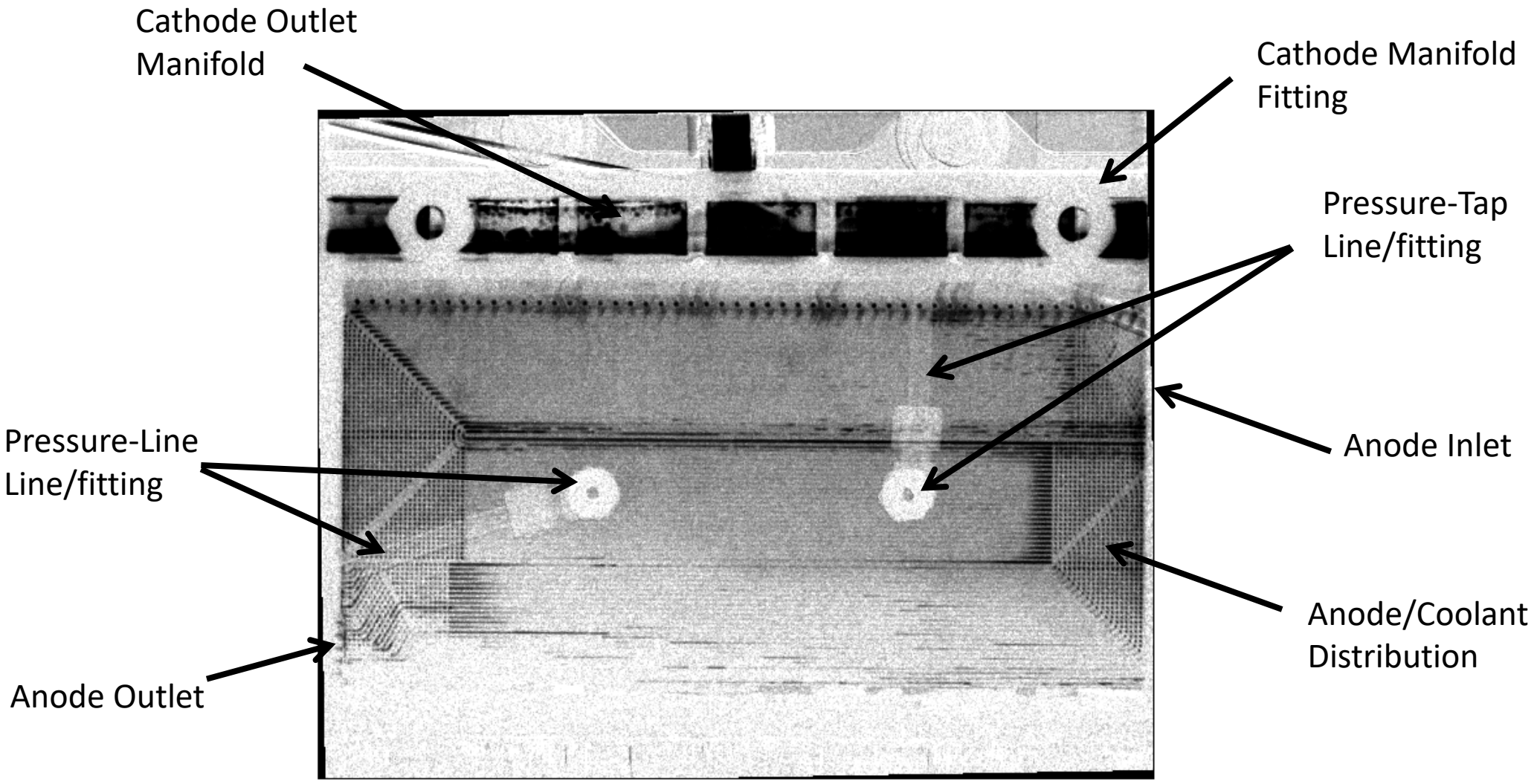
	Stack Current amps	T(cool-out) C	coolant DT C	*Ano Stoic*	Ano P **(in)** kPa	*Ano-in RH %*	*Ano-in N2% %*	Cat Stoic	Cat P **(in)** kPa	Cat P **(out)** kPa	Cat-in RH %	Cat RH-out %
	12.5	58	2	*4.0*	150	*100%*	*23%*	1.60	101	101	dry	132%
	50.0	58	2	*1.7*	150	*100%*	*22%*	1.60	105	102	dry	133%
	70.0	58	2	*1.7*	155	*100%*	*22%*	1.60	107	102	dry	133%
	87.5	61	2	*1.7*	160	*100%*	*21%*	1.55	108	103	dry	120%
	105.0	61	3	*1.6*	160	*100%*	*19%*	1.55	110	103	dry	120%
	125.0	64	3	*1.6*	170	*100%*	*17%*	1.55	122	115	dry	117%
	150.0	61	4	*1.5*	170	*100%*	*16%*	1.55	137	130	dry	151%
	225.0	75	6	*1.5*	185	*100%*	*17%*	1.54	190	180	dry	113%
	312.5	80	8	*1.5*	200	*100%*	*13%*	1.53	200	180	dry	93%
	450.0	80	10	*1.4*	225	*100%*	*11%*	1.53	220	195	dry	100%
Excursion	325.0	92	8	*1.4*	180	*100%*	*11%*	1.33	204	190	dry	69%

- Stack runs to as high as 500 A in transients. Use same operating conditions as 450 A
- Anode-inlet RH assumes at coolant-in T and anode RH-out is 100%. May be somewhat lower, especially at max CD, recommend sensitivity studies.
- Anode-inlet N2% is calculated using estimated 75% anode-out H2% and estimated anode stoic
- Can use either cat-in or cat-out for P-control. DP will depend on stoic, operating conditions, etc.
- Cat RH-out is information only. Inlet is dry, control to T(cool-out).

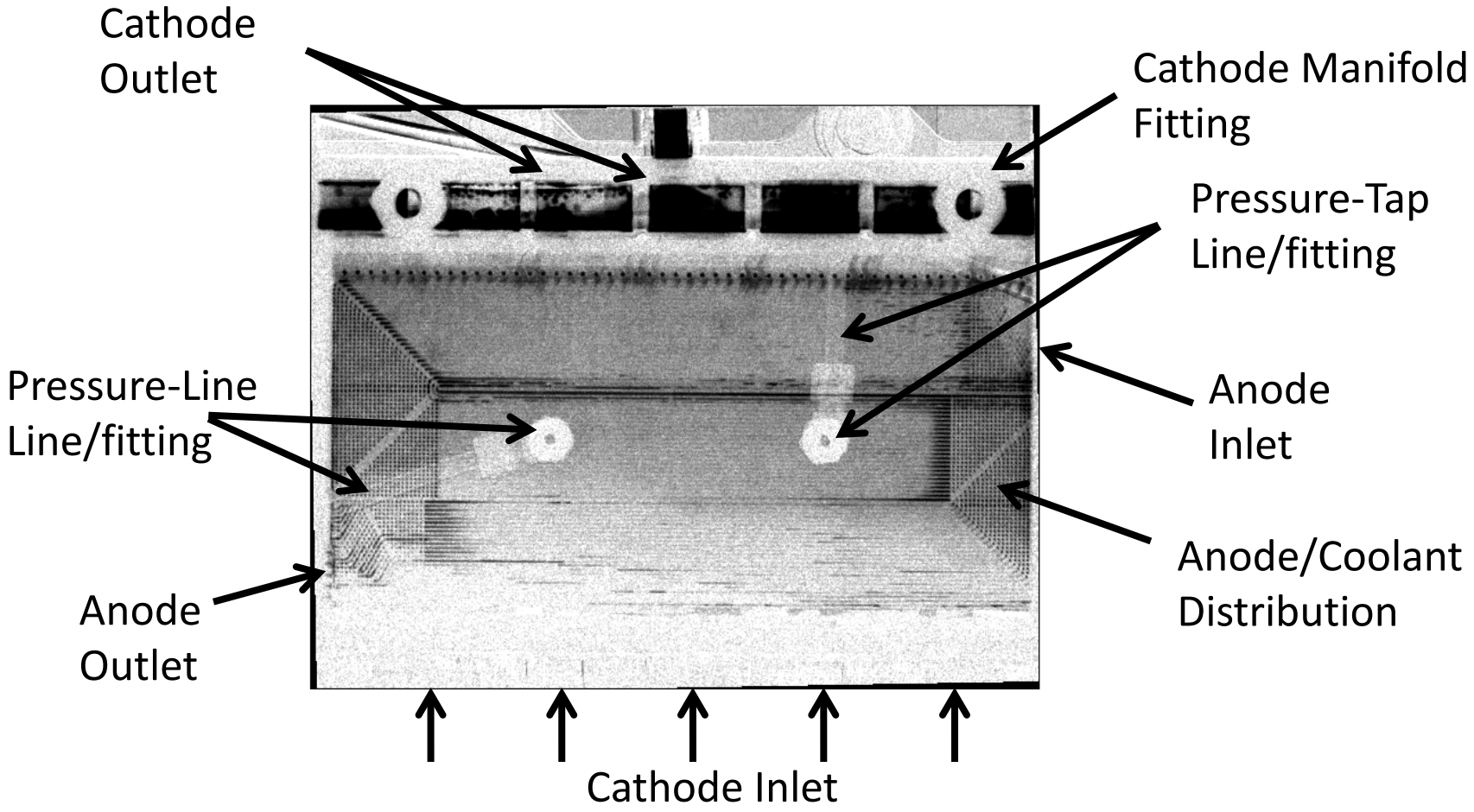
In addition –

- *Isothermal/Isobaric polarization curves at 60C and 80C*
- *RH Sensitivity: Anode and Cathode*
- *Stoich Sensitivity: Anode and Cathode*

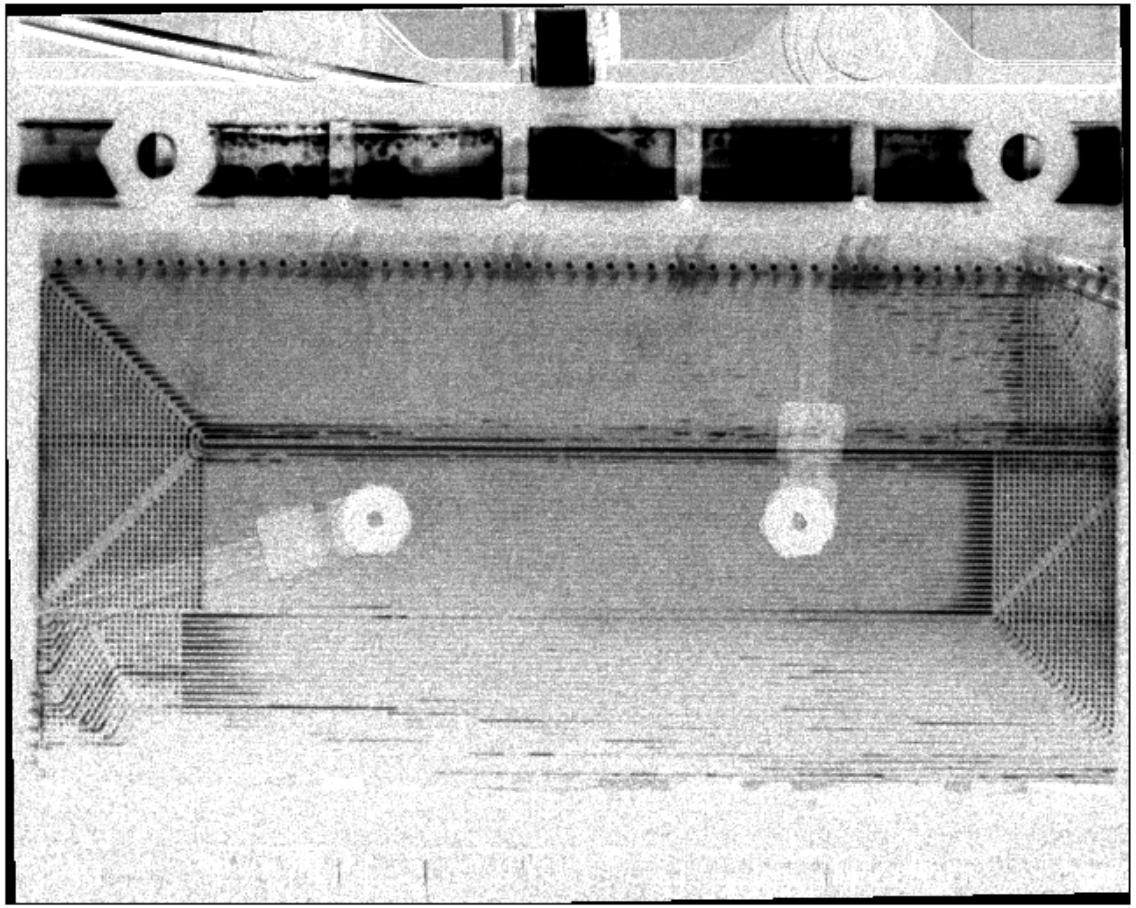
Base Neutron Image of 5-Cell Mirai Short Stack

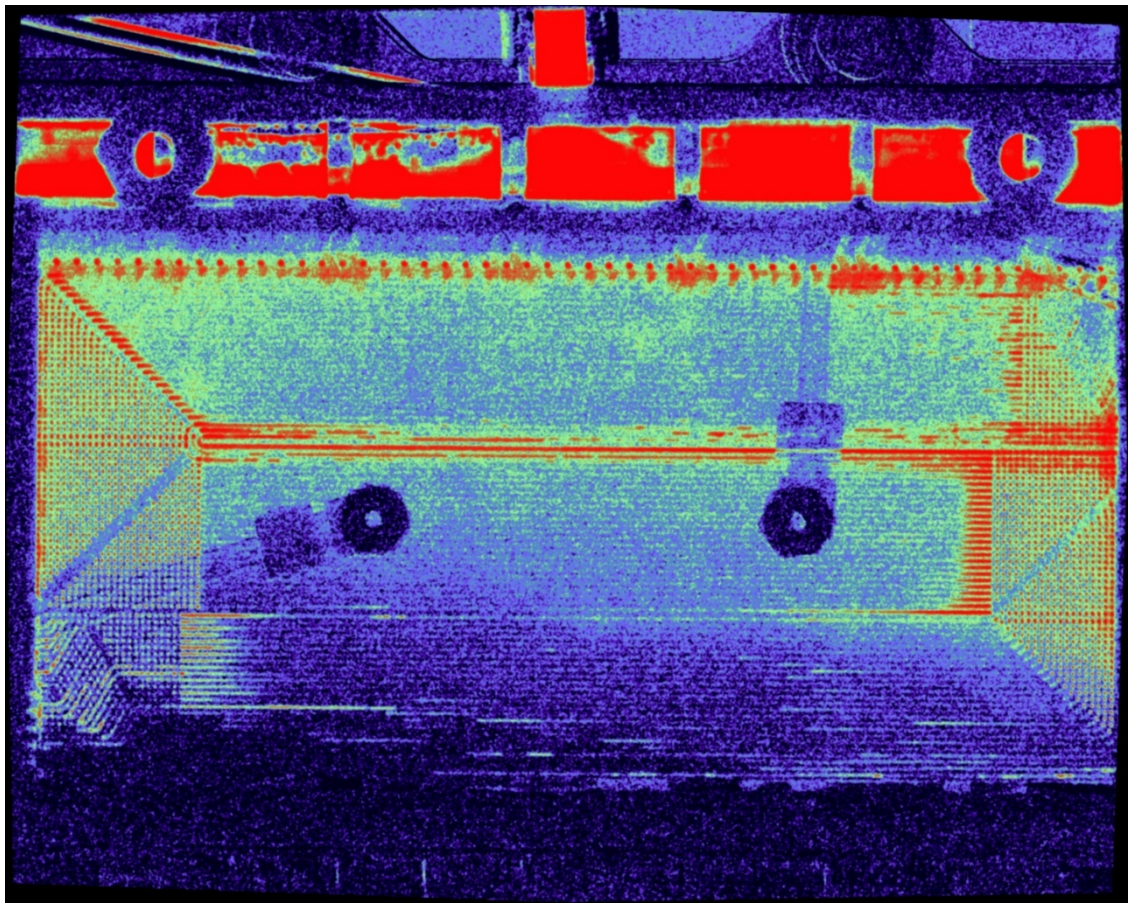


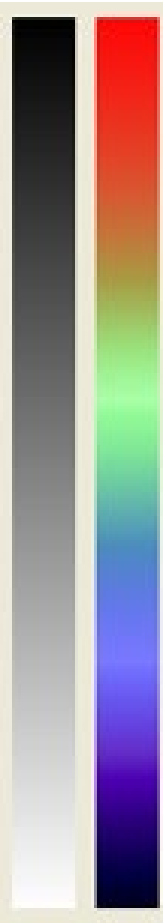
Neutron Image of 5-Cell Mirai Short Stack



Colorized Water Image of 5-Cell Mirai Short Stack



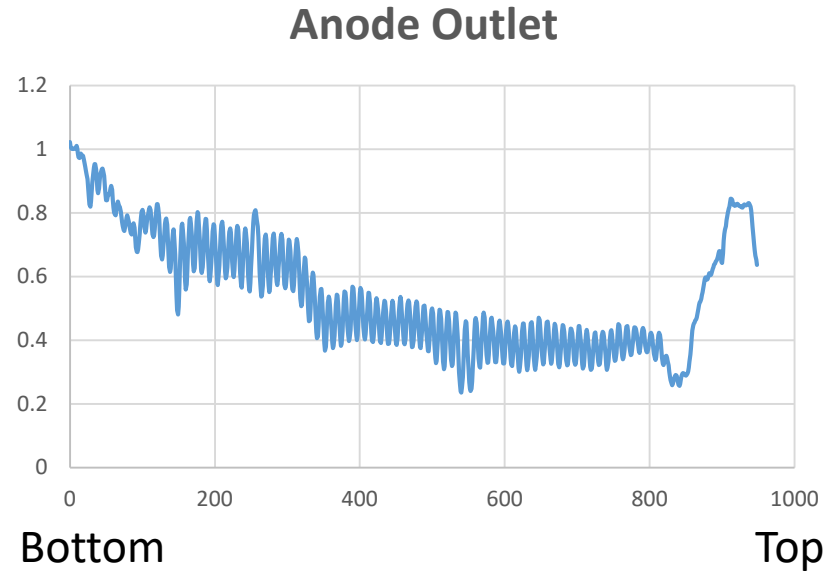


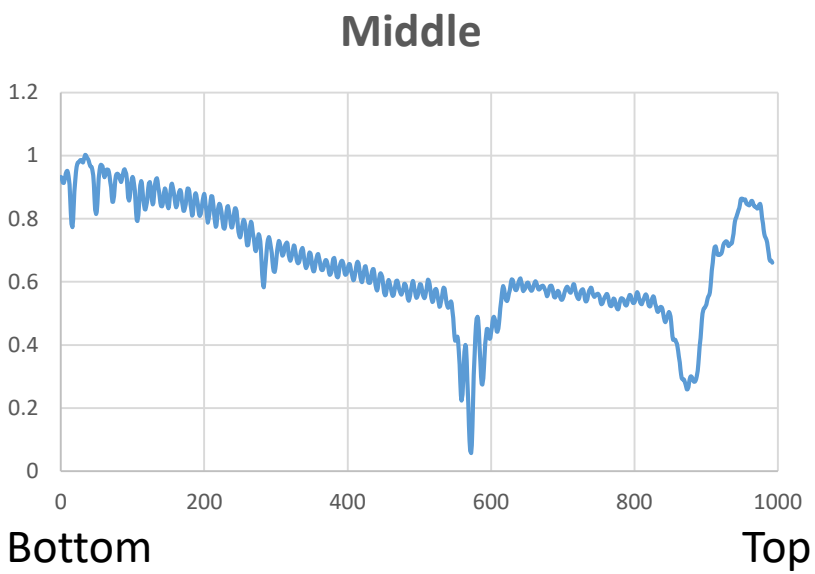


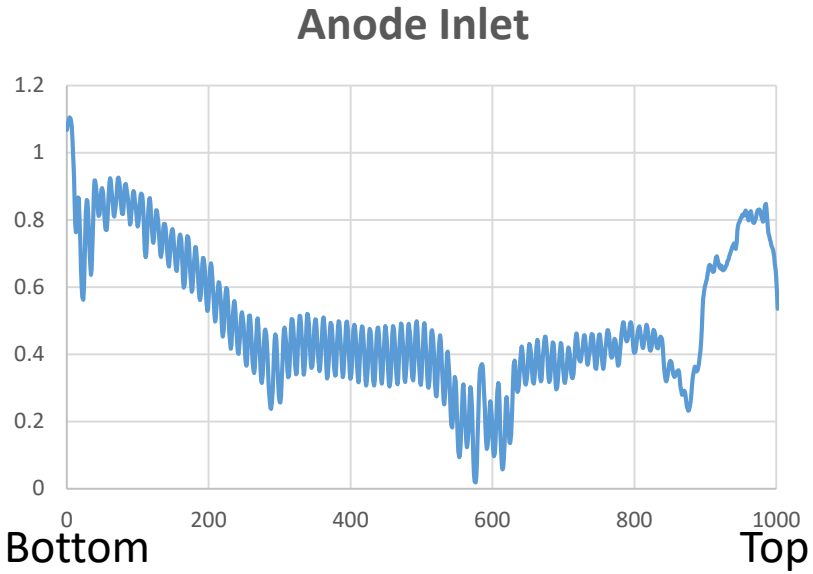
Due to ‘issues’ during imaging, not all colorization is identical; however it is consistent within each separate matrix

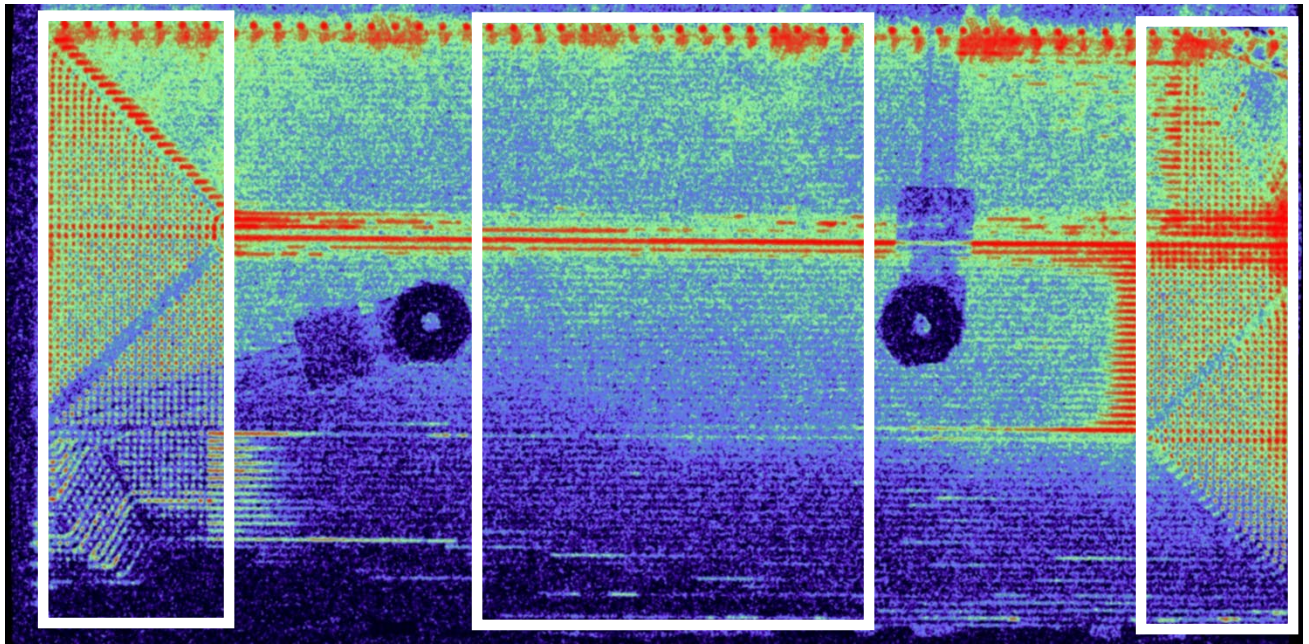
Water Line profiles

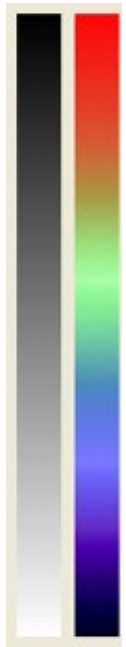
(Don’t really show much obvious that isn’t visual)





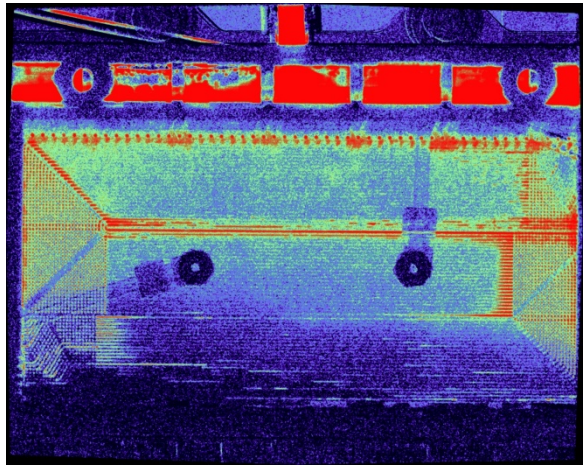




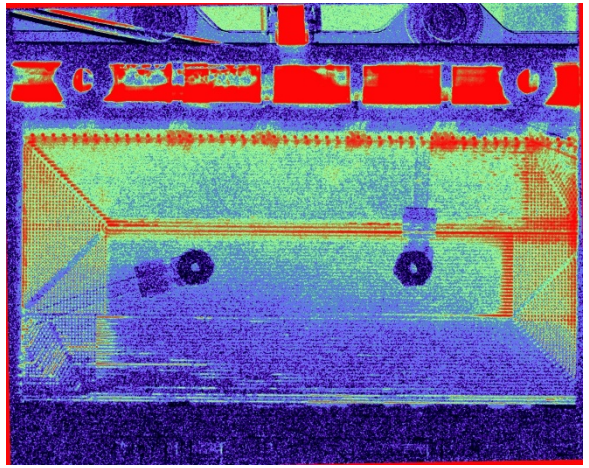


USCAR Matrix of Operating Conditions

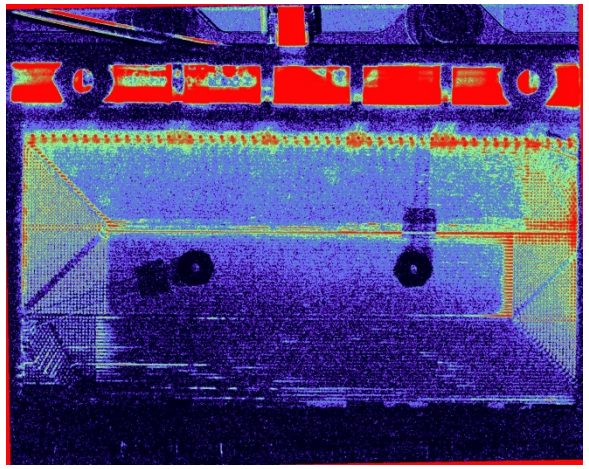
50A



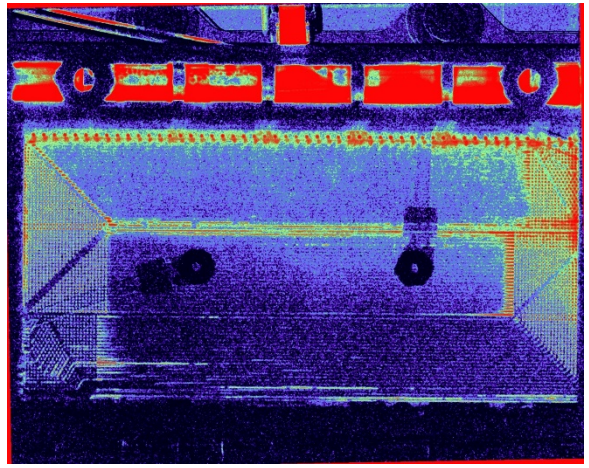
70A



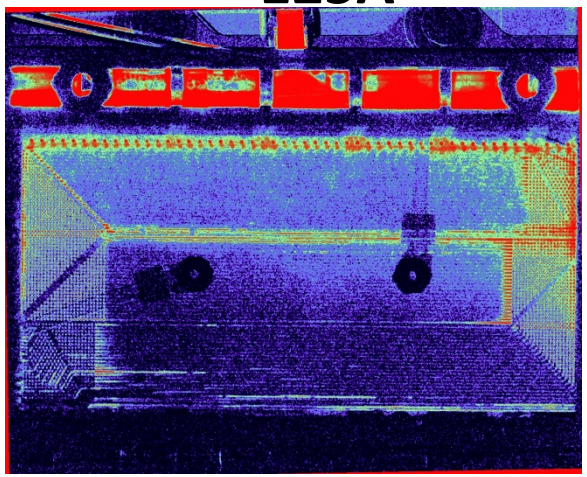
87.5A



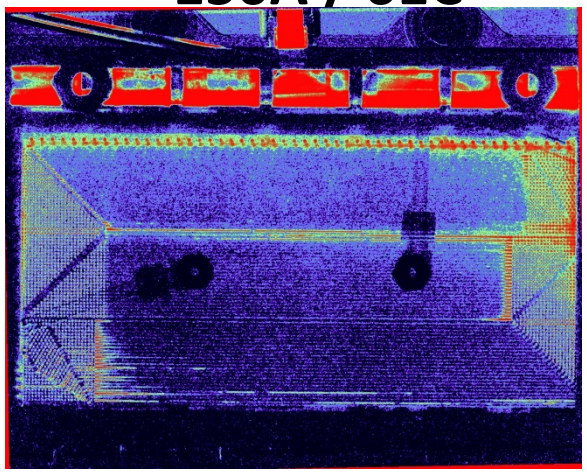
105A



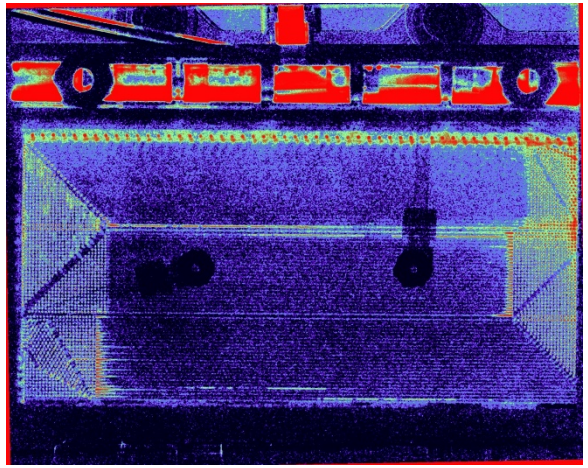
125A



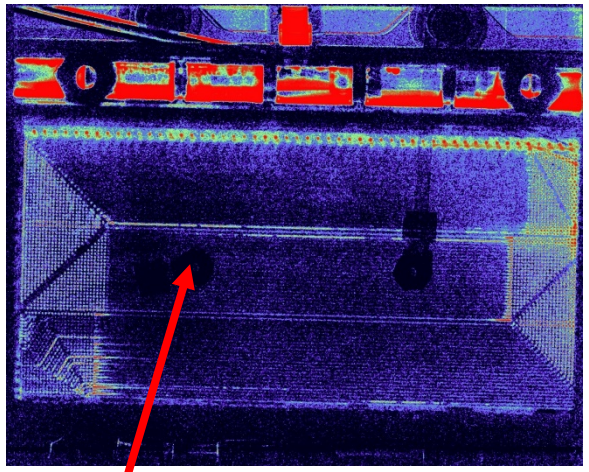
150A / 61C



225A



312A



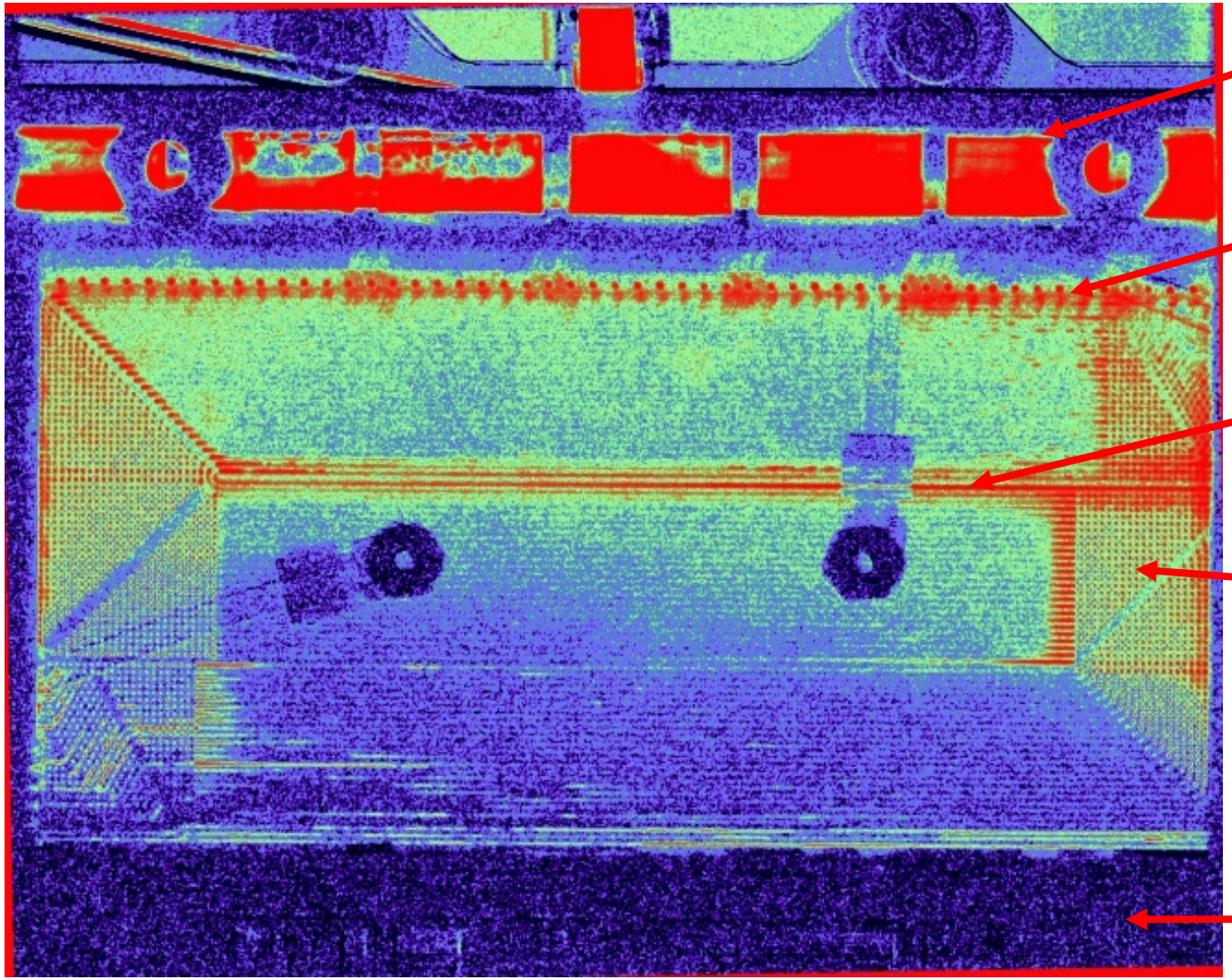
Notes: ***12.5 Amp point, unstable***

450 Amp point insufficient H2

High Current & Flowrates show much less liquid water than low current/flowrates

Comment on Water Images

High Current & Flowrates show much less liquid water than low current/flowrates
→ Cathode does not show flooding limitations at high power
→ Low power does show flooding, and instabilities



Cathode outlet manifold always has water

Cathode outlet active area edge always shows liquid water

At Anode segment 1 and 2 interface always has liquid water present

Anode/coolant mixing/distribution shows liquid water; amount varies with flowrate

Cathode inlet manifold never has water

70A

Isothermal and Isobaric Polarization Curves at 80C and 60C

100%RH anode/ dry cath.
Variable stoich + N2 composition (USCAR matrix)
200/200 kPa An/Ca outlet pressures

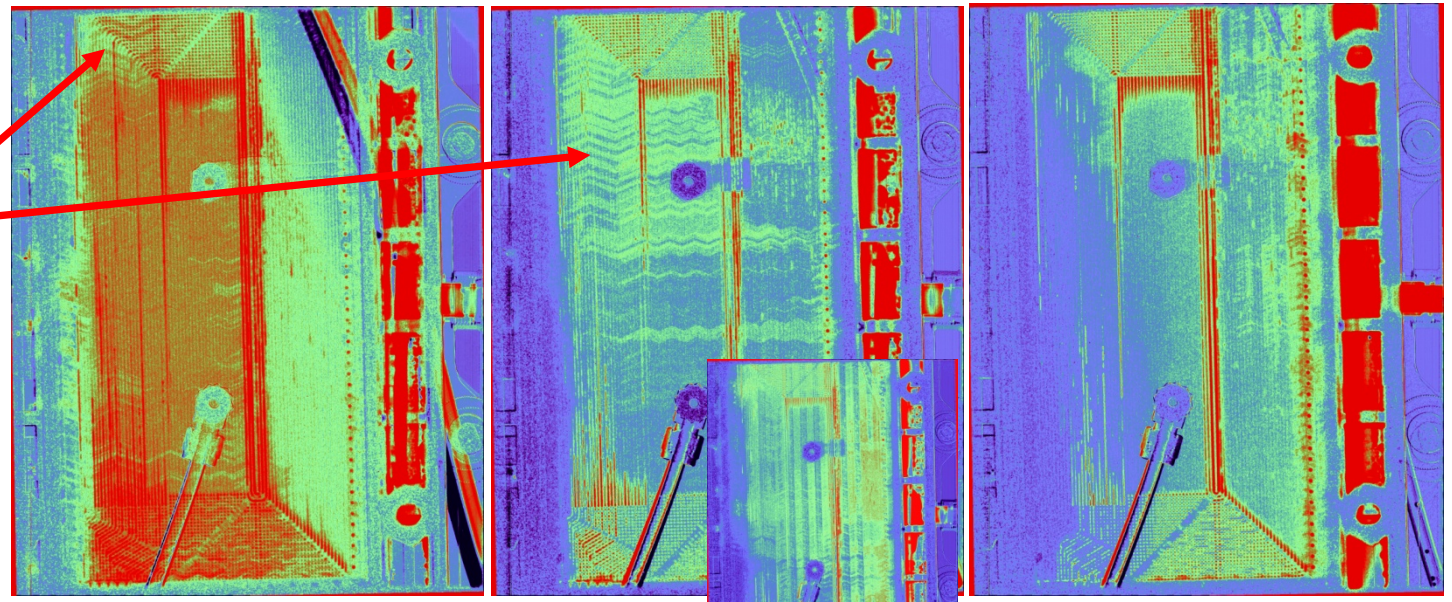
80C Pol Curve: Lower Currents

Increasing current

12.5A

25A (redo)

50A



At Low currents,
cathode water exists

1st:

Flooded; not stable

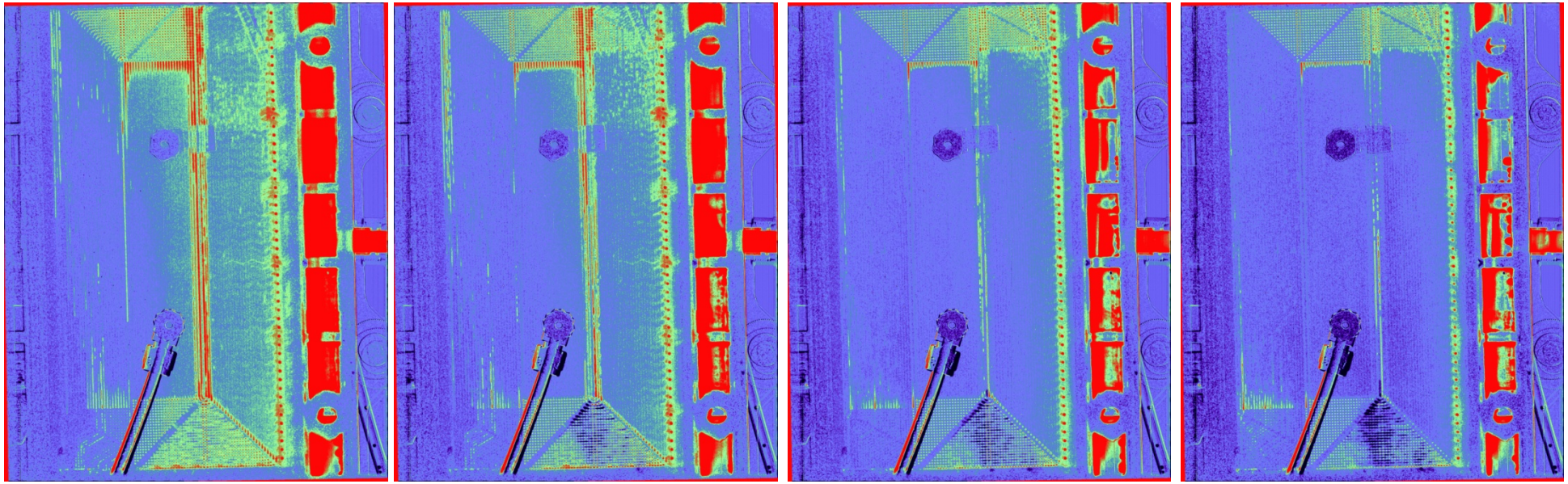
Decreasing water

100%RH anode/ dry cath.
Variable stoich + N2 composition (USCAR matrix)
200/200 kPa An/Ca outlet pressures

80C pol curve: Higher currents

Increasing current

70A 125A 225A 350A



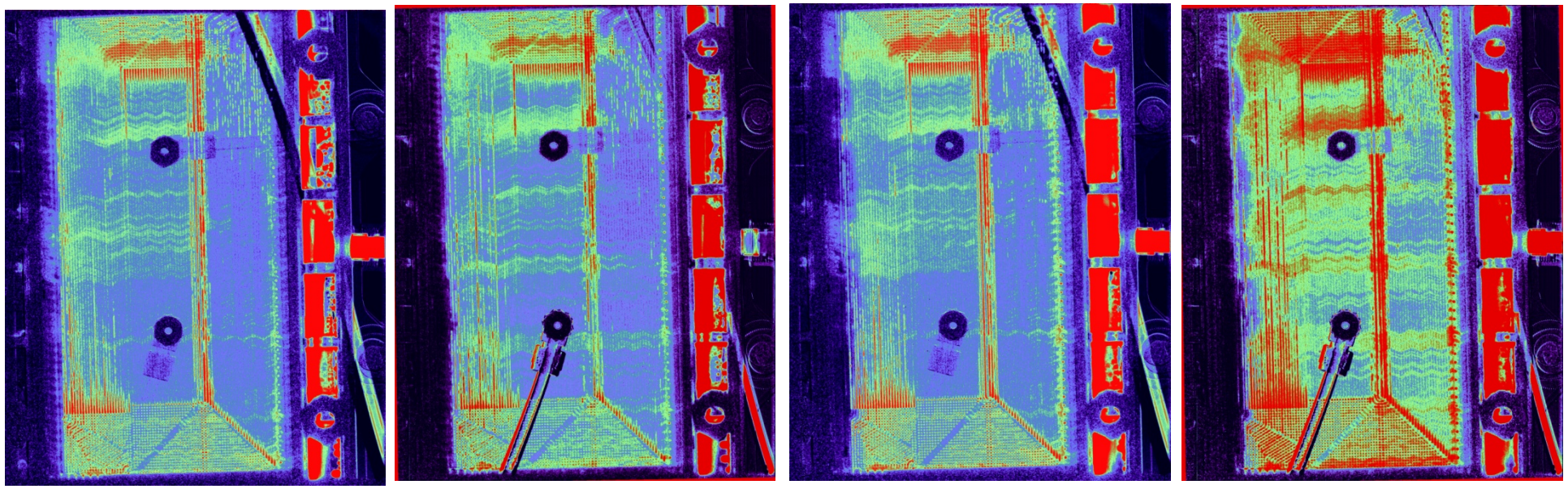
Decreasing water

100%RH anode/ dry cath.
Variable stoich + N2 composition (USCAR matrix)
200/200 kPa An/Ca outlet pressures

60C Pol Curve: Lower Currents

Increasing current

25A | 25A (redo) | 50A | 50A (redo)



Anode stoich: 3 | Anode stoich: 3 | Anode stoich: 1.7 | Anode stoich: 1.7

Increasing water

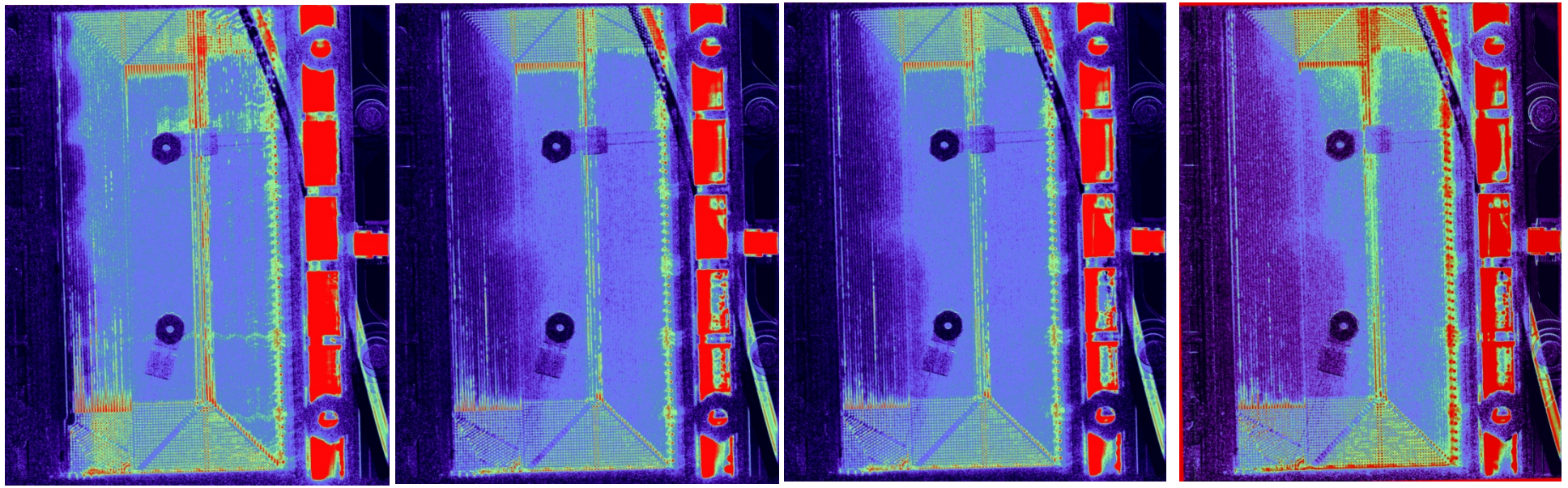
No 12.5A at 60C due to instable operation (flooding)

100%RH anode/ dry cath.
Variable stoich + N2 composition (USCAR matrix)
200/200 kPa An/Ca outlet pressures

60C Pol Curve: Higher Currents

Increasing current

70A 125A 225A 350A



Decreasing water

Similar water

Increasing water

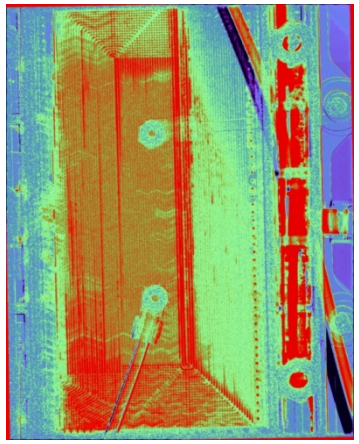
100%RH anode/ dry cath.
Variable stoich + N2 composition (USCAR matrix)
200/200 kPa An/Ca outlet pressures

Higher currents do not show large water build-up/flooding even at 60 C

Operating Temperature Comparison

80C

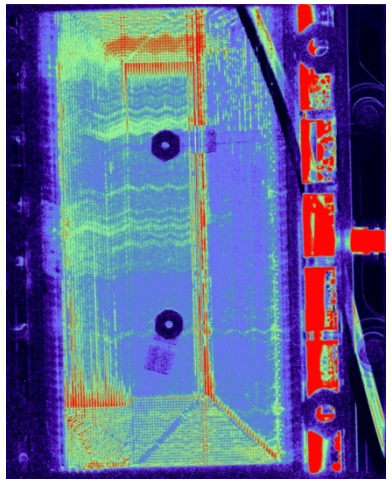
12.5A (80C)



(Not stable at 60C)
H_2+N_2 = 3.5 slpm

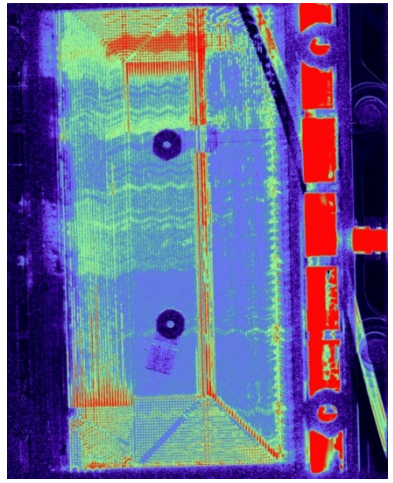
60C Initial Sequence

25A



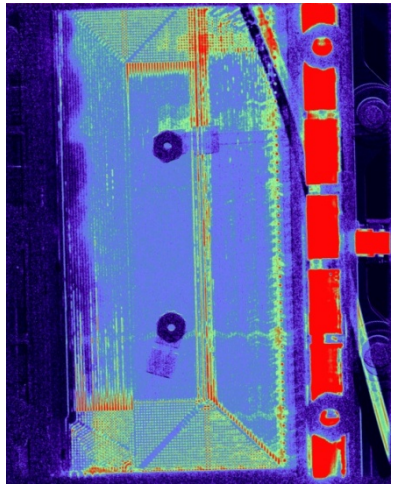
Anode stoich: 3
H_2+N_2 = 3.5 slpm

50A



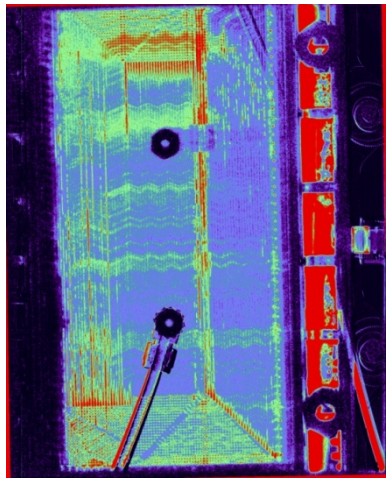
Anode stoich: 1.7
H_2+N_2 = 3.9 slpm

70A

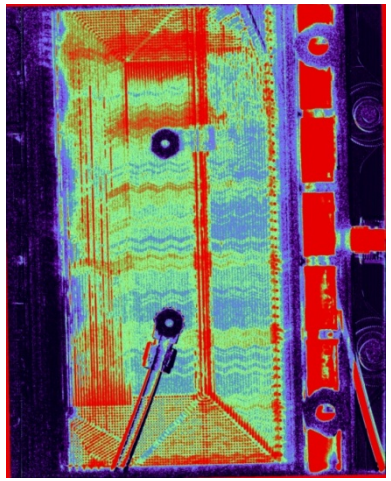


Anode stoich: 1.7
H_2+N_2 = 5.5 slpm

25A (redo)



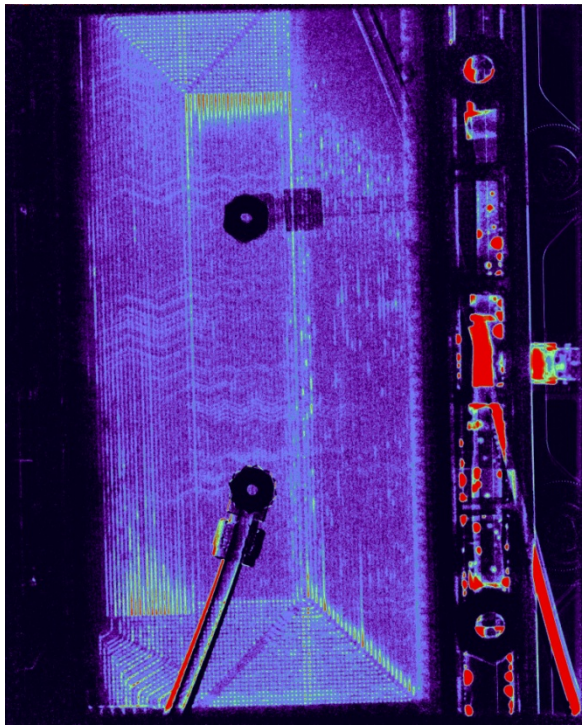
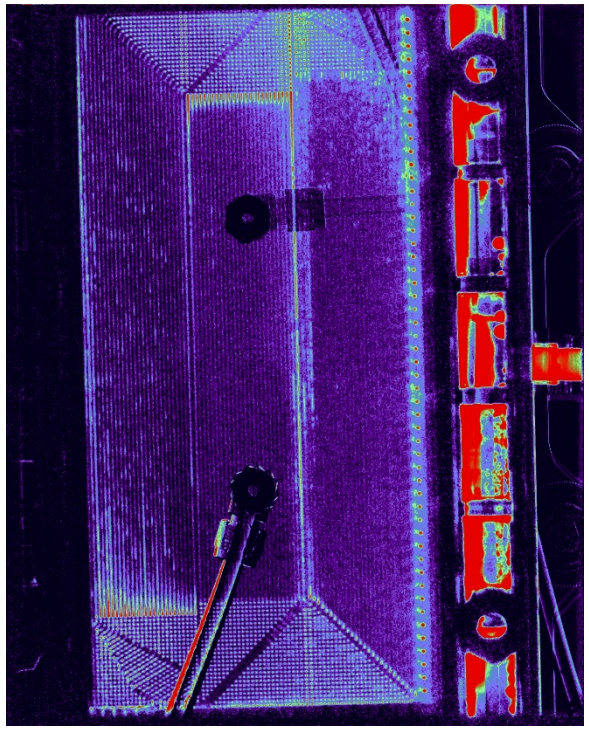
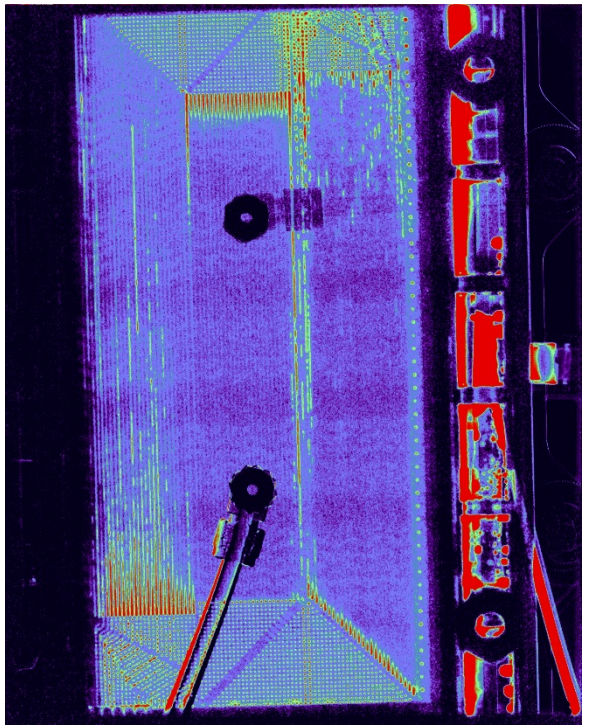
50A (redo)



Cathode stoich = 1.55
Cathode – Dry
Anode – 100% RH

Sensitivity to RH, Stoich, and Temperature

60C “Transient” Operation

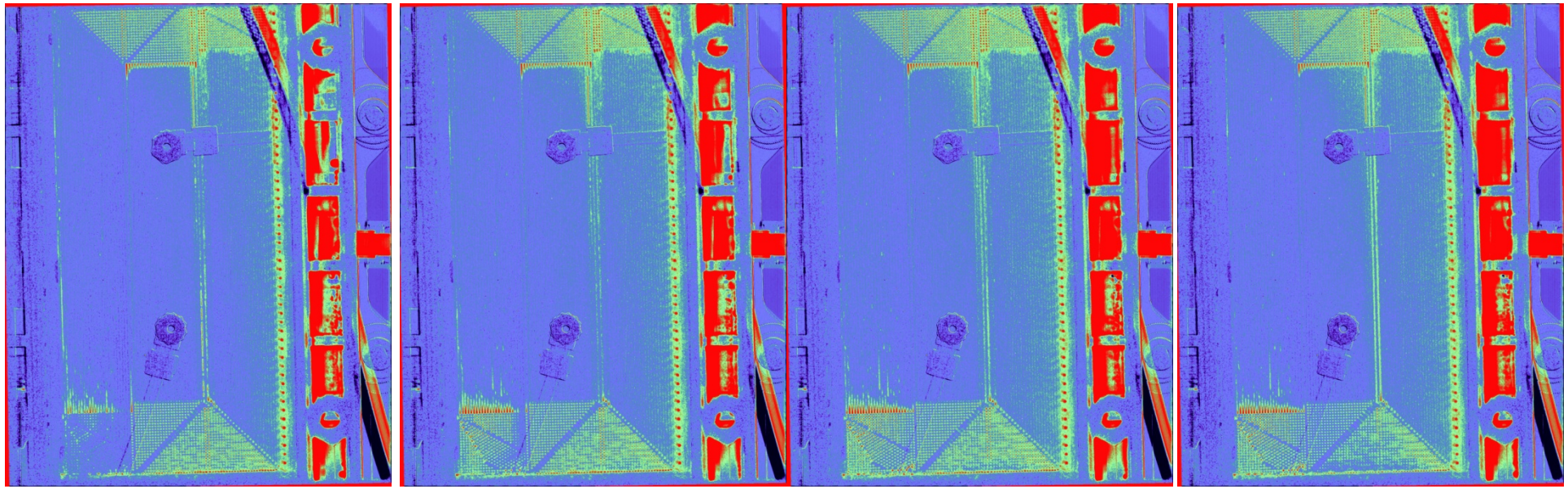




- 10 min intervals: 25A → 300A → 25A

80C Cathode Stoich Sensitivity (250A)

Decreasing cathode stoich.

1.6 1.4 1.2 1.1



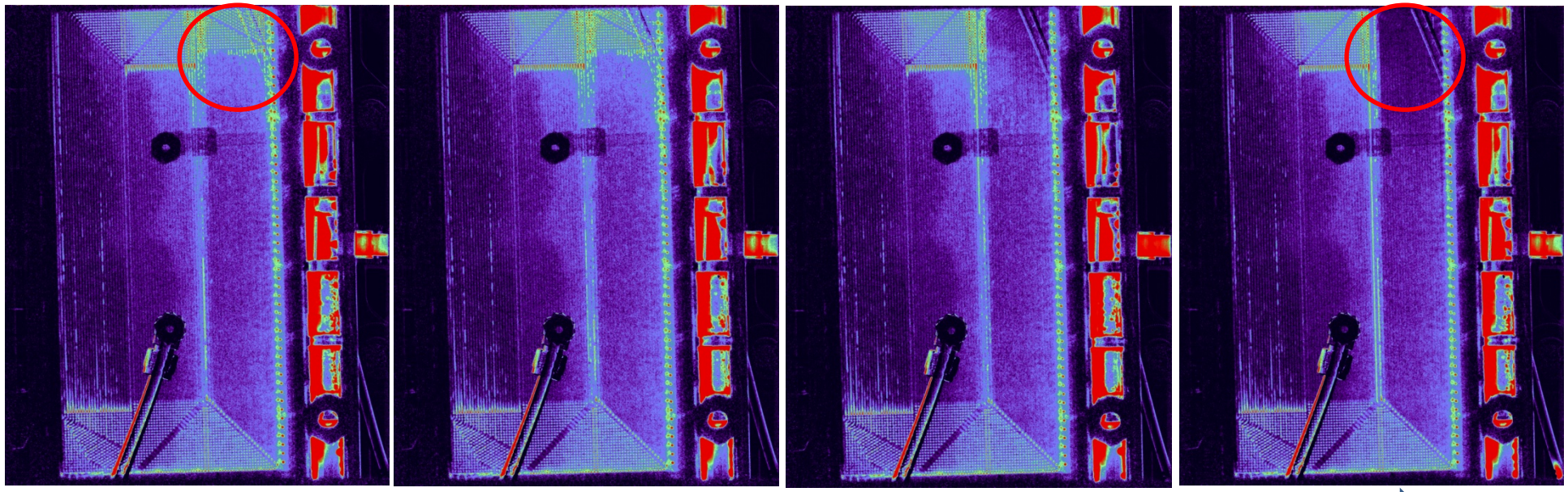
Increasing water? … need to quantify

250 A, 100%RH anode/ dry cath.
1.6 An stoich
200/200 kPa An/Ca outlet pressures

60C Anode RH Sensitivity

Decreasing anode RH

100%RH 80%RH 60%RH 40%RH



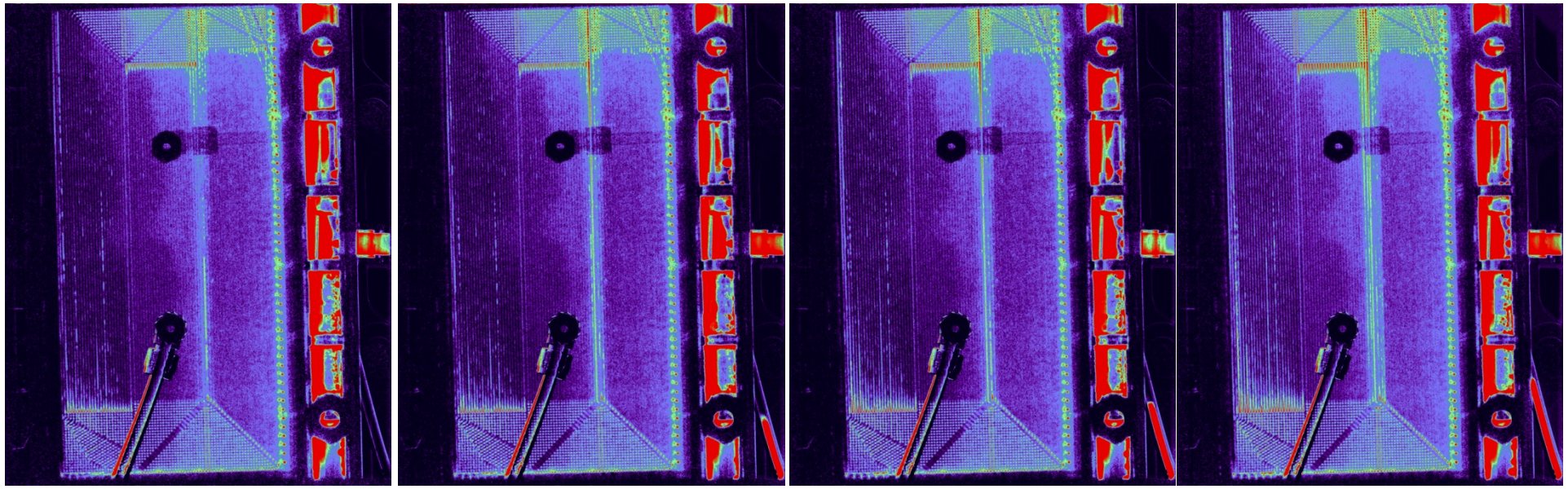
Decreasing water at Anode Inlet

250 A, dry cathode
1.6/1.55 An/Ca stoich
200/200 kPa An/Ca outlet pressures

60C Anode Stoich Sensitivity

Decreasing anode stoich.

1.6 1.4 1.2 1.1



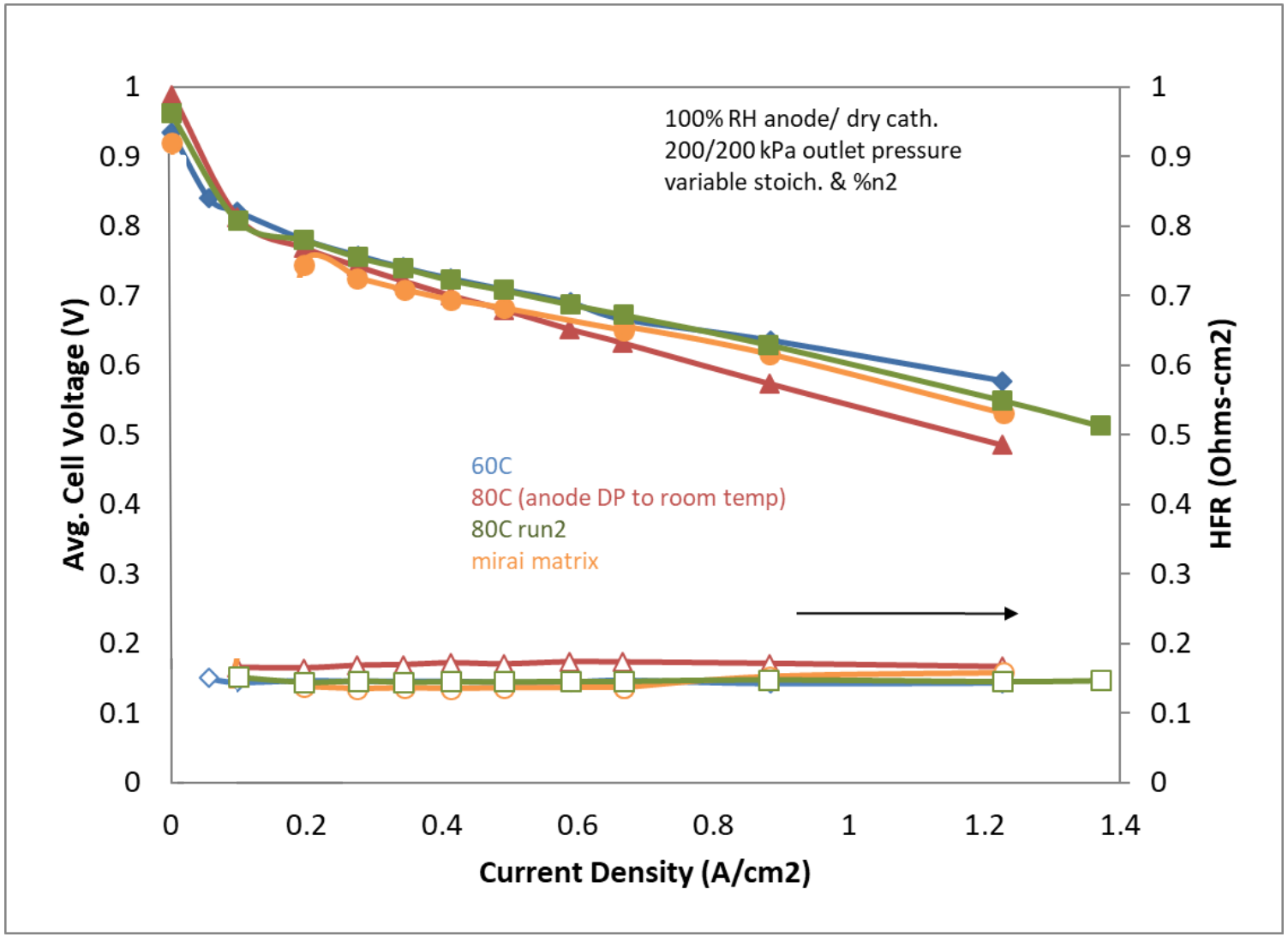
Decreasing water

Similar water

Increasing water

250 A, 100%RH anode/ dry cath.
1.55 Ca stoich
200/200 kPa An/Ca outlet pressures

Polarization Curves at 60C and 80C



Selected Conclusions

[Conditions related to USCAR Provided Toyota Mirai operating conditions]

- Liquid water primarily on Anode side
- All conditions show some water; especially at 2/3 serpentine interface and cathode outlet weld area
- Anode Inlet/outlet (and Cooling serpentine returns) show water build-up. This area is logical area for both distribution problems (low current) and possible durability concerns such as carbon corrosion
- Stack water is primarily sensitive to anode flowrate

Selected Conclusions

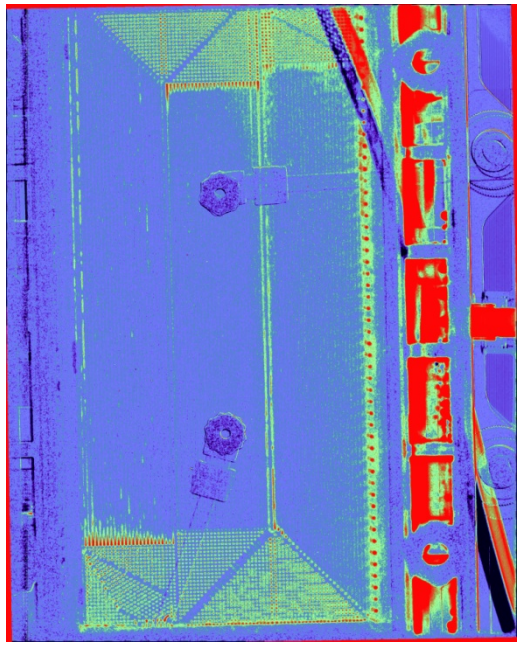
[RH, Stoich, Temp sensitivity Tests]

- Stack water is relatively insensitive to cathode RH and stoichiometry (to 1.1)
- Low current/low anode flowrates show liquid water on cathode
  - Water cross-over to cathode appears to be logical cause
- Response time of stack to water is long compared to drive cycle conditions
- Low current/temperature points were primarily unstable during operation; are possibly more problematic;
  - (How does this car idle? Stack probably has to either turn off or run at higher power than idle ……)
- Liquid water is primarily (almost always on anode). A few points should be examined for corrosion.
- Mirai stack design seems well designed for operation at high currents/flowrates. Flooding does not seem an issue at high currents.

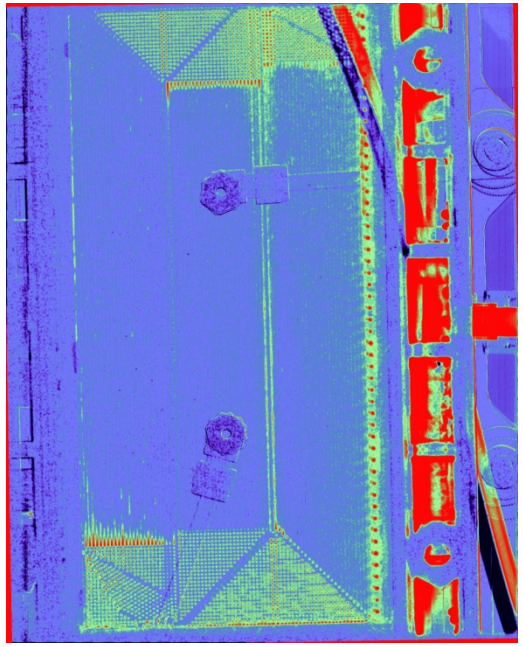
80C Cathode RH Sensitivity (250A)

Decreasing cathode RH

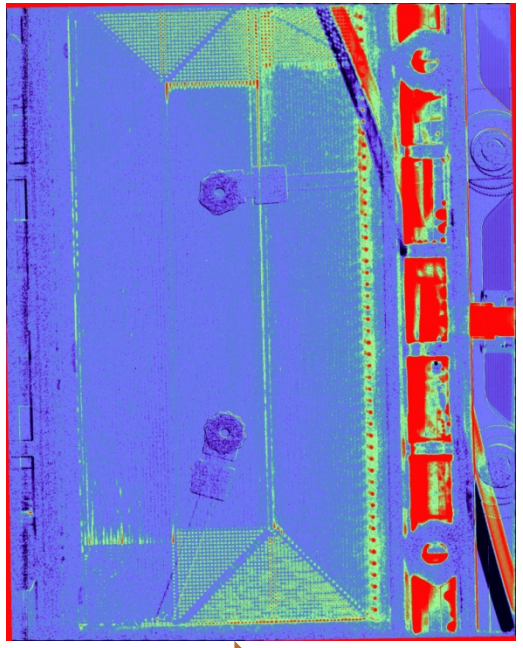
40%RH



20%RH



dry



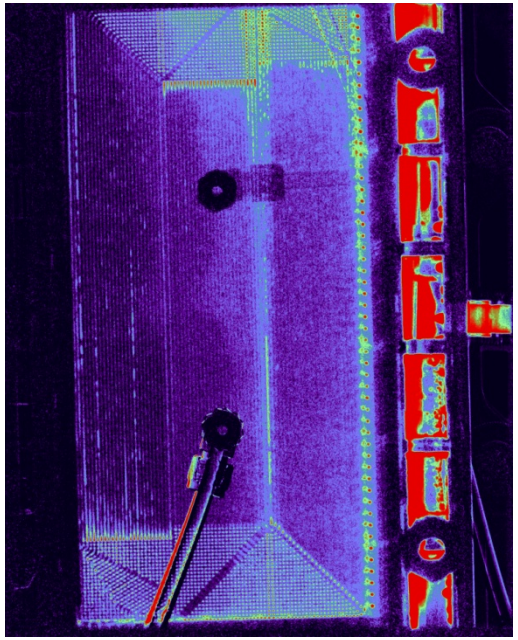
Similar water

250 A, 100%RH anode
1.6/1.55 An/Ca stoich
200/200 kPa An/Ca outlet pressures

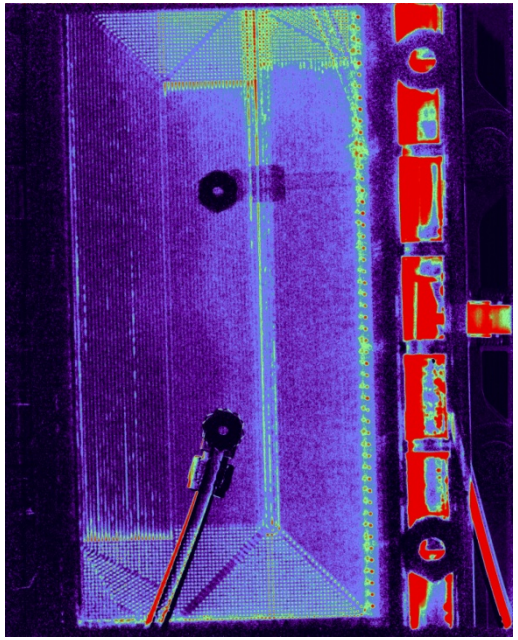
60C Cathode Stoich Sensitivity

Decreasing cathode stoich.

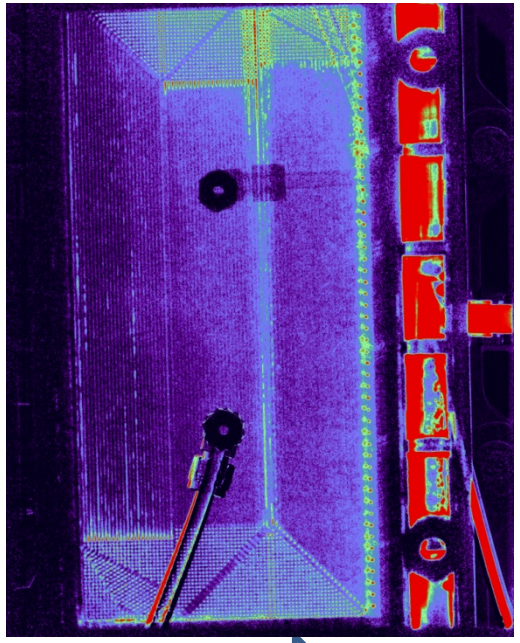
1.55



1.4



1.2



Increasing water? … need to quantify

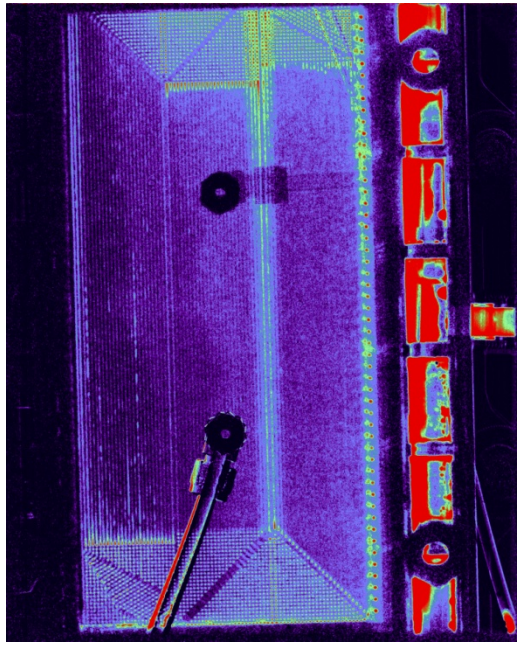
250 A, 100%RH anode/ dry cath.
1.6 An stoich
200/200 kPa An/Ca outlet pressures

Good Operation at Cathode stoich of 1.2!

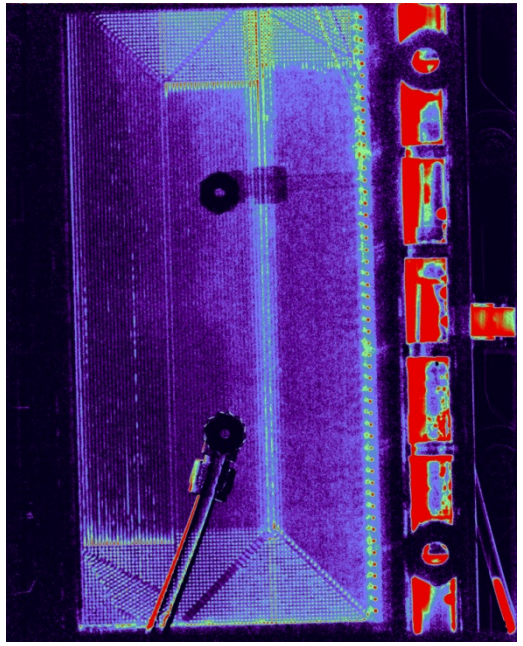
60C Cathode RH Sensitivity

Decreasing cathode RH

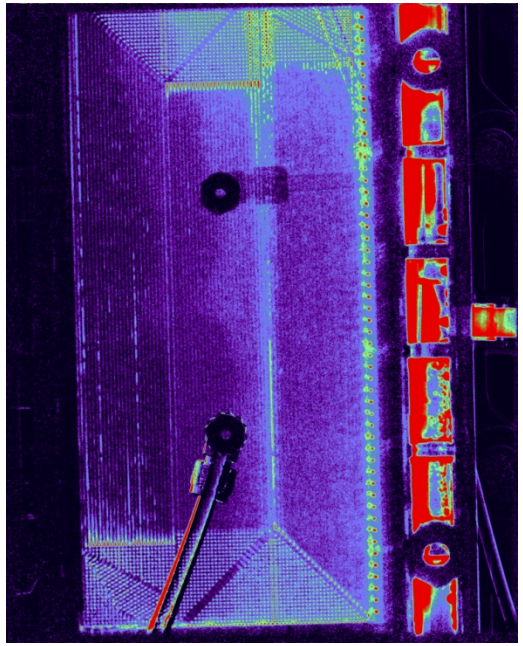
40%RH



20%RH



dry



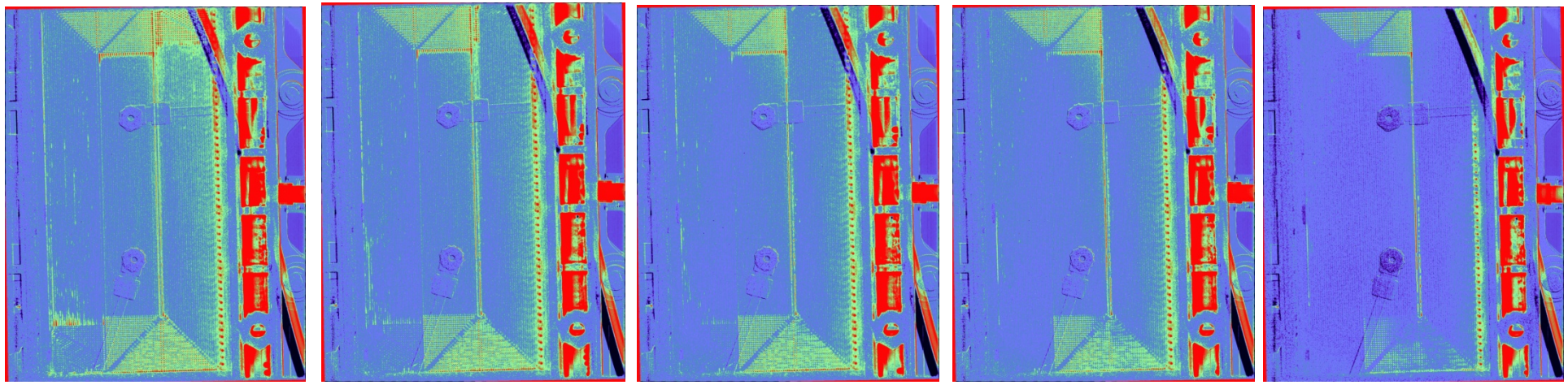
Similar water

250 A, 100%RH anode
1.6/1.55 An/Ca stoich
200/200 kPa An/Ca outlet pressures

80C Anode RH Sensitivity

Decreasing anode RH

100%RH 80%RH 60%RH 40%RH 20%RH



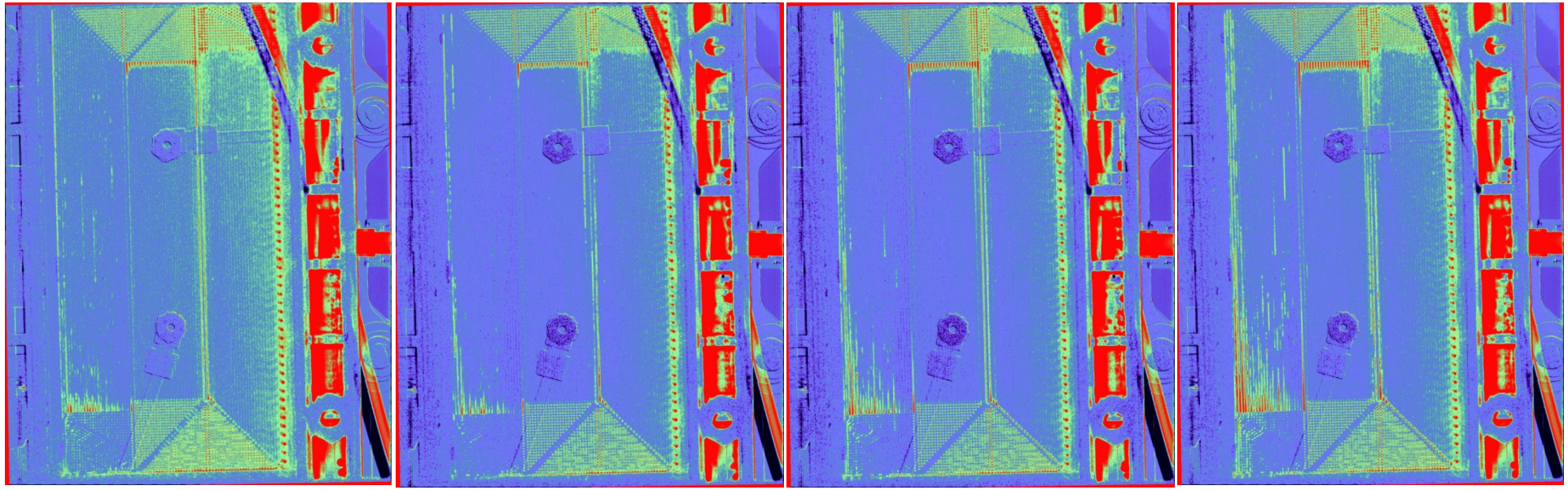
Decreasing water

250 A, dry cathode
1.6/1.55 An/Ca stoich
200/200 kPa An/Ca outlet pressures

80C Anode Stoich Sensitivity (250A)

Decreasing anode stoich.

1.6 1.4 1.2 1.1



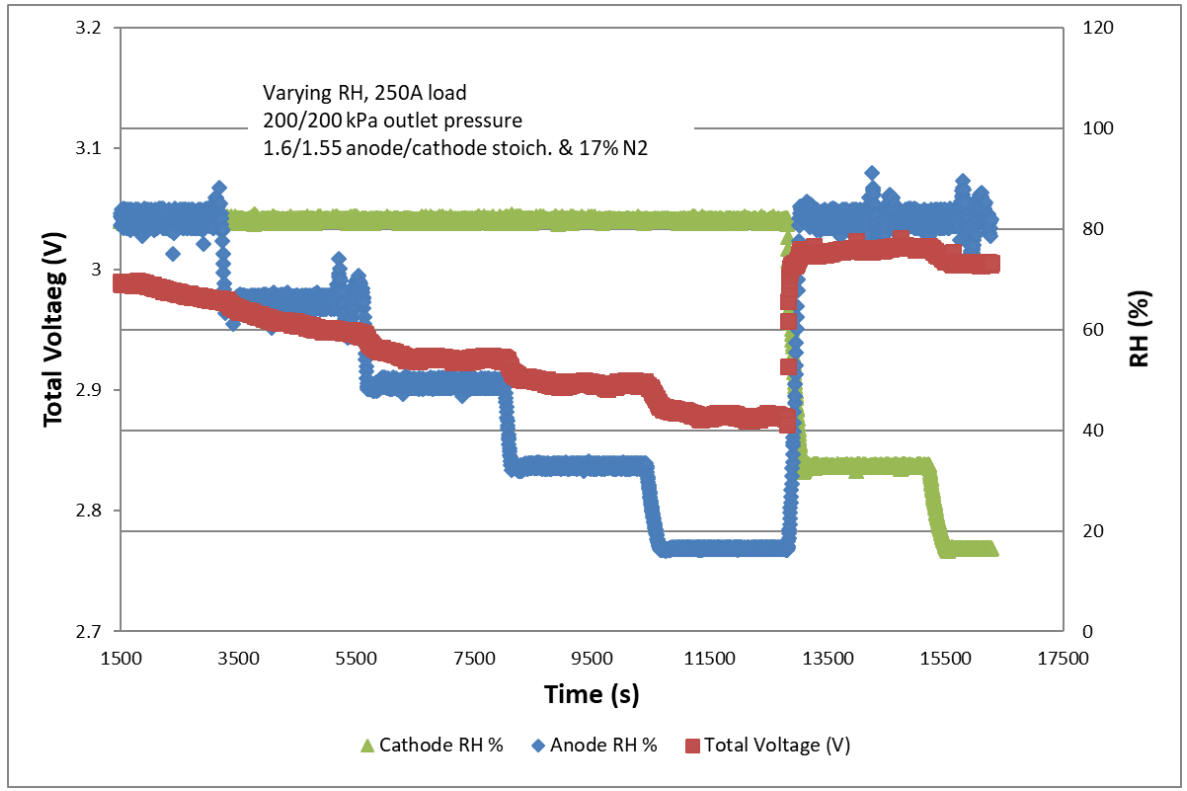
Decreasing water

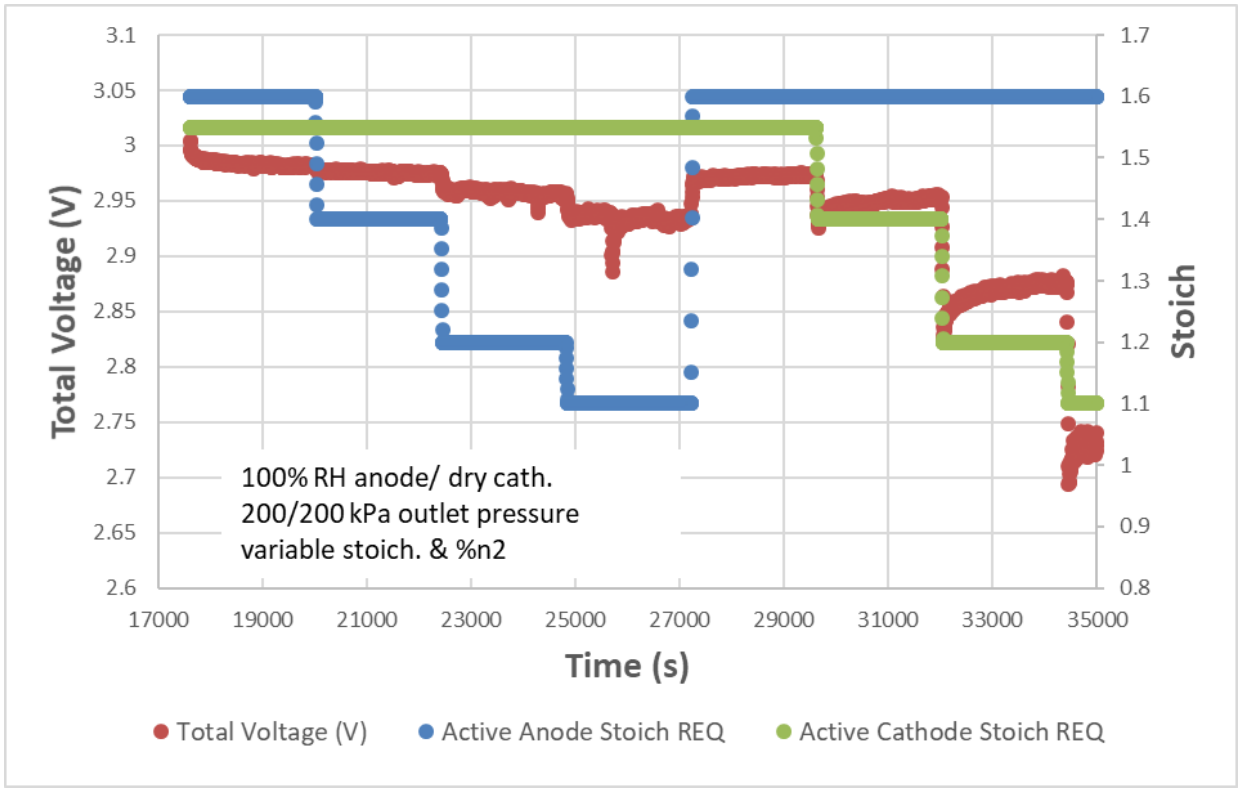
Similar water

Increasing water

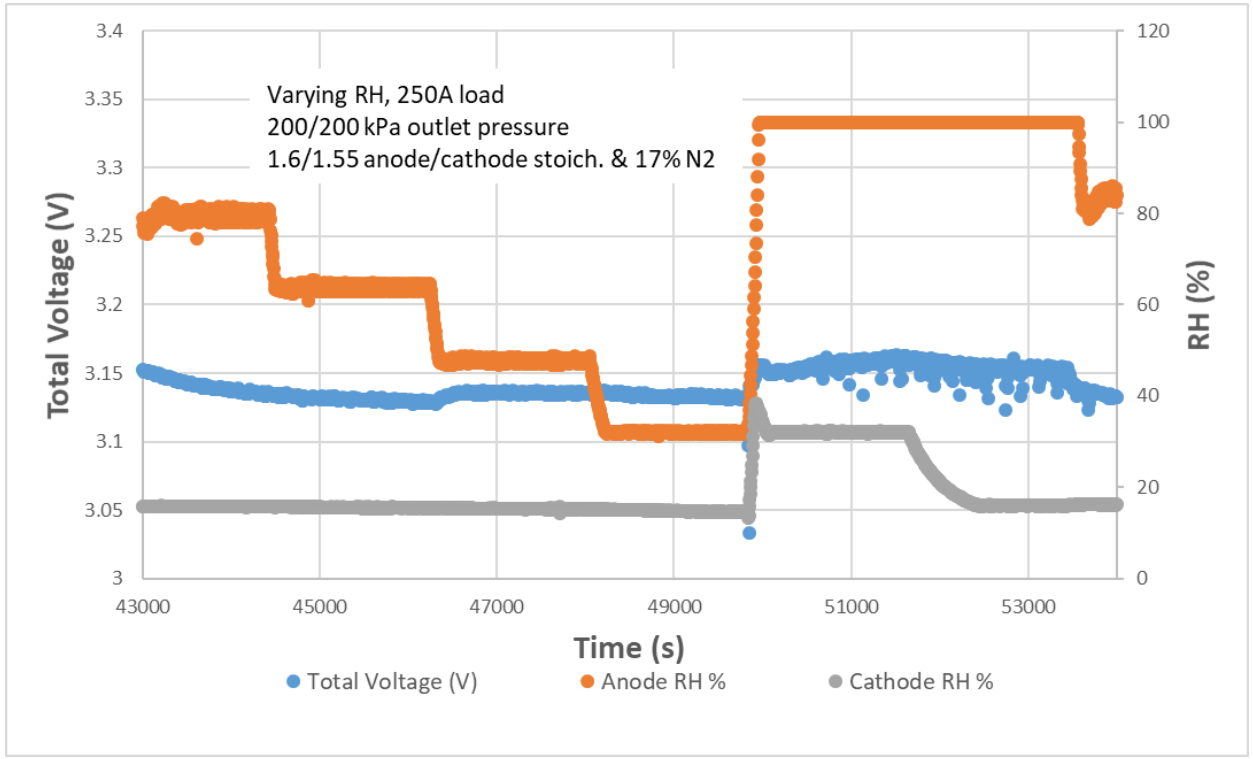
250 A, 100%RH anode/ dry cath.
1.55 Ca stoich
200/200 kPa An/Ca outlet pressures

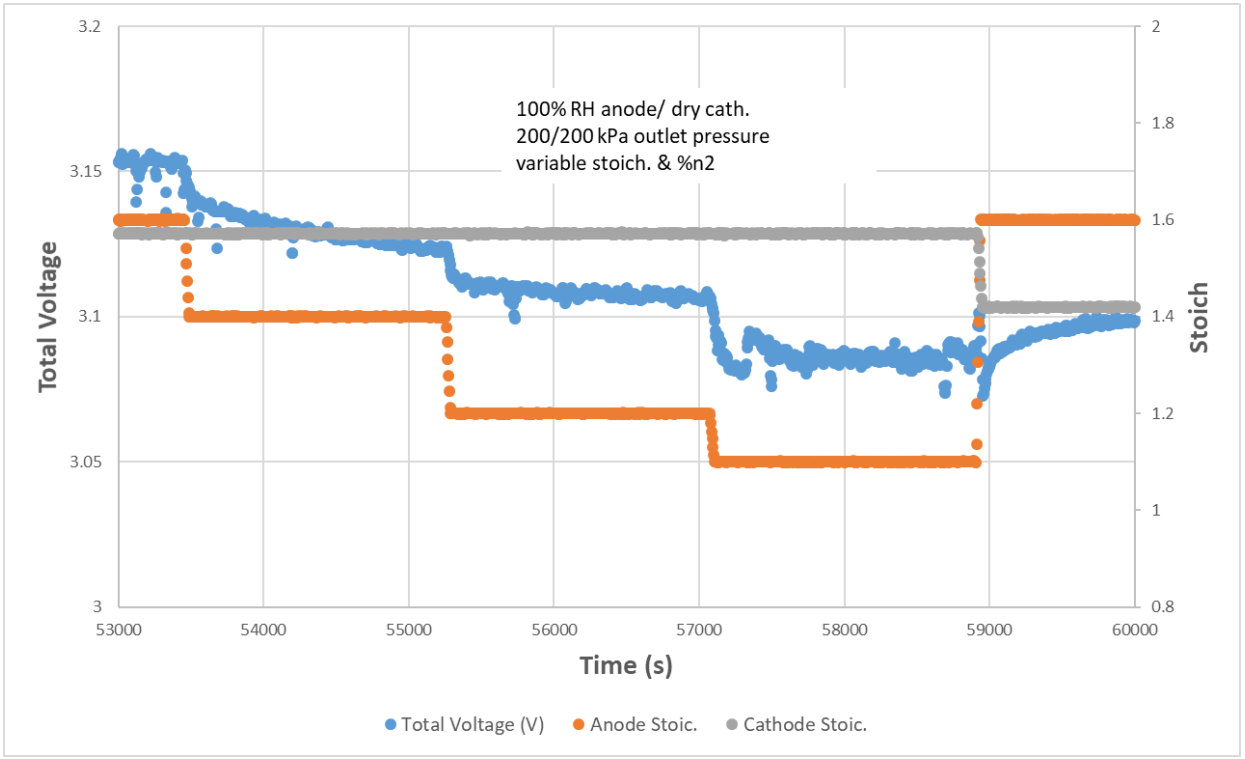
RH & Stoich vs. Total Voltage at 80C



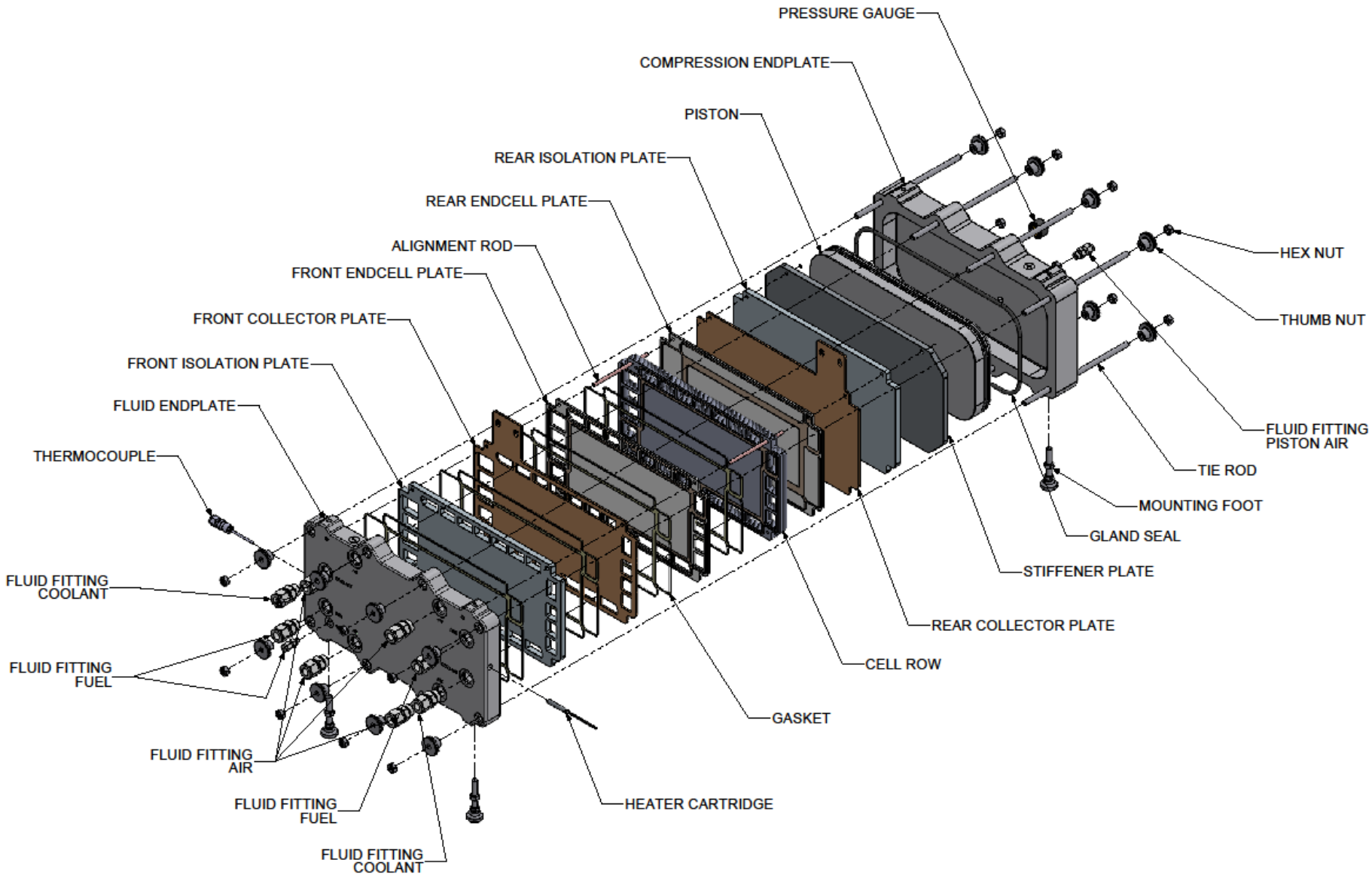


RH & Stoich vs. Total Voltage at 60C



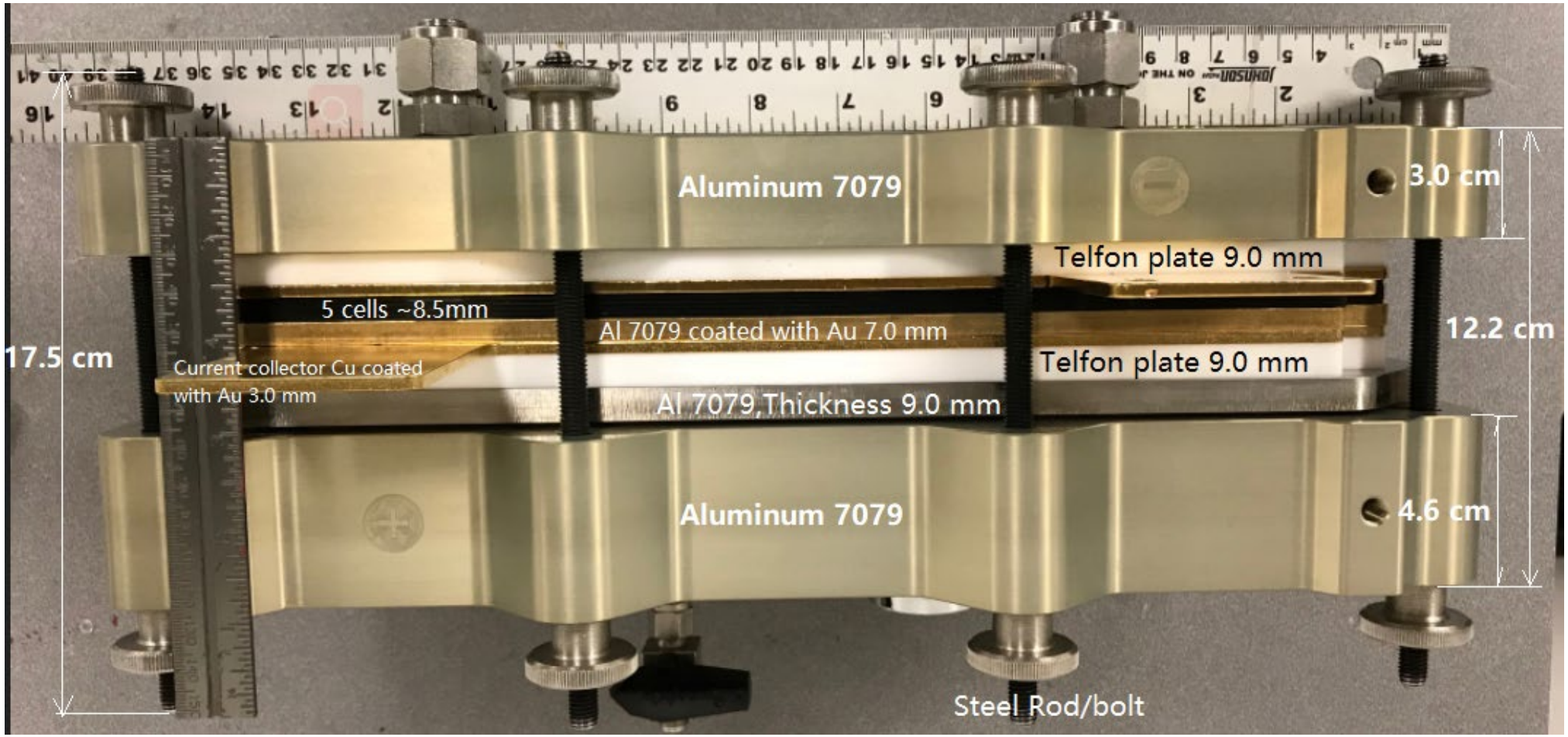


Toyota Short-stack Compression Hardware Exploded View

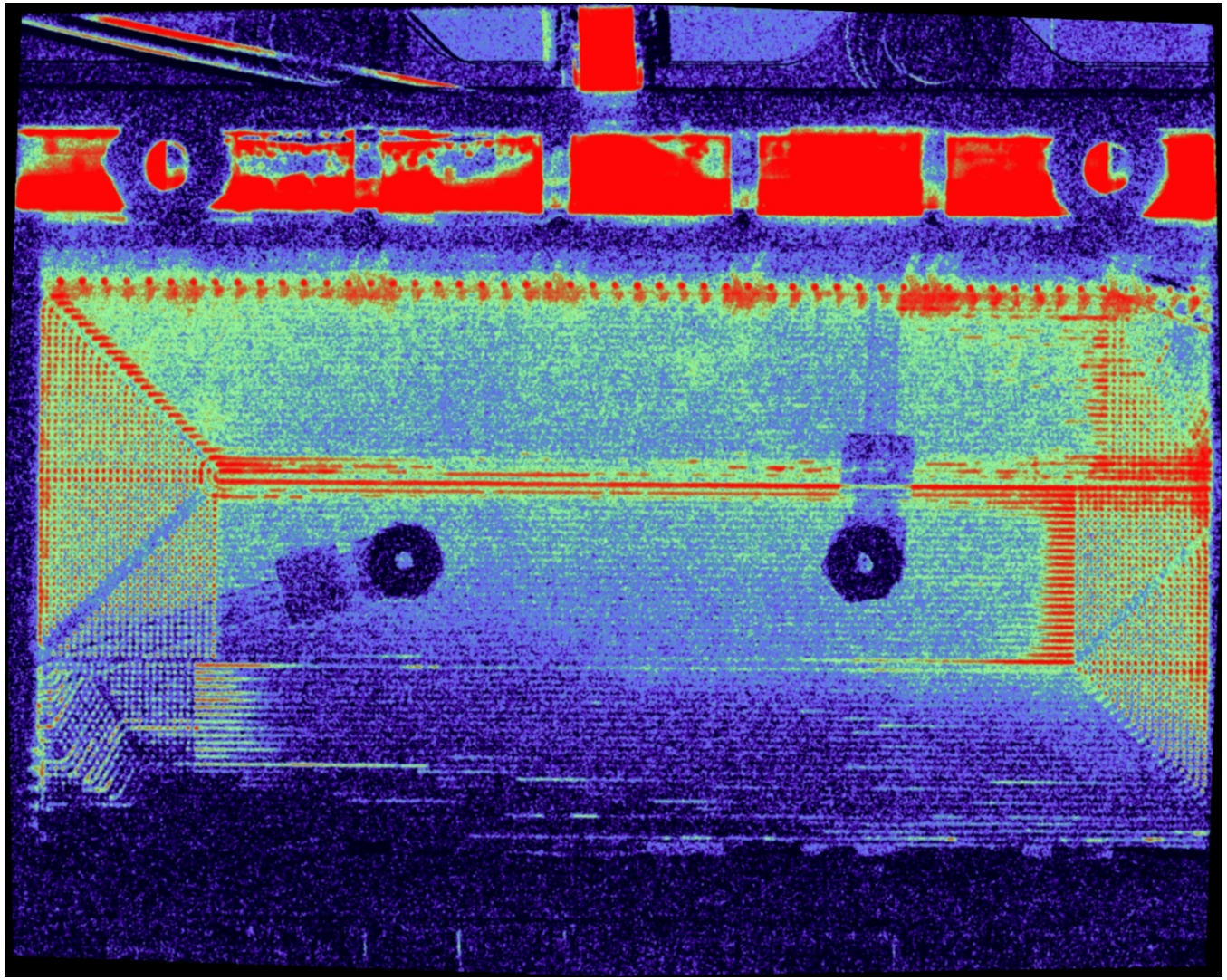


Toyota Mirai 5 Cell Short-Stack Dimensions/ Materials

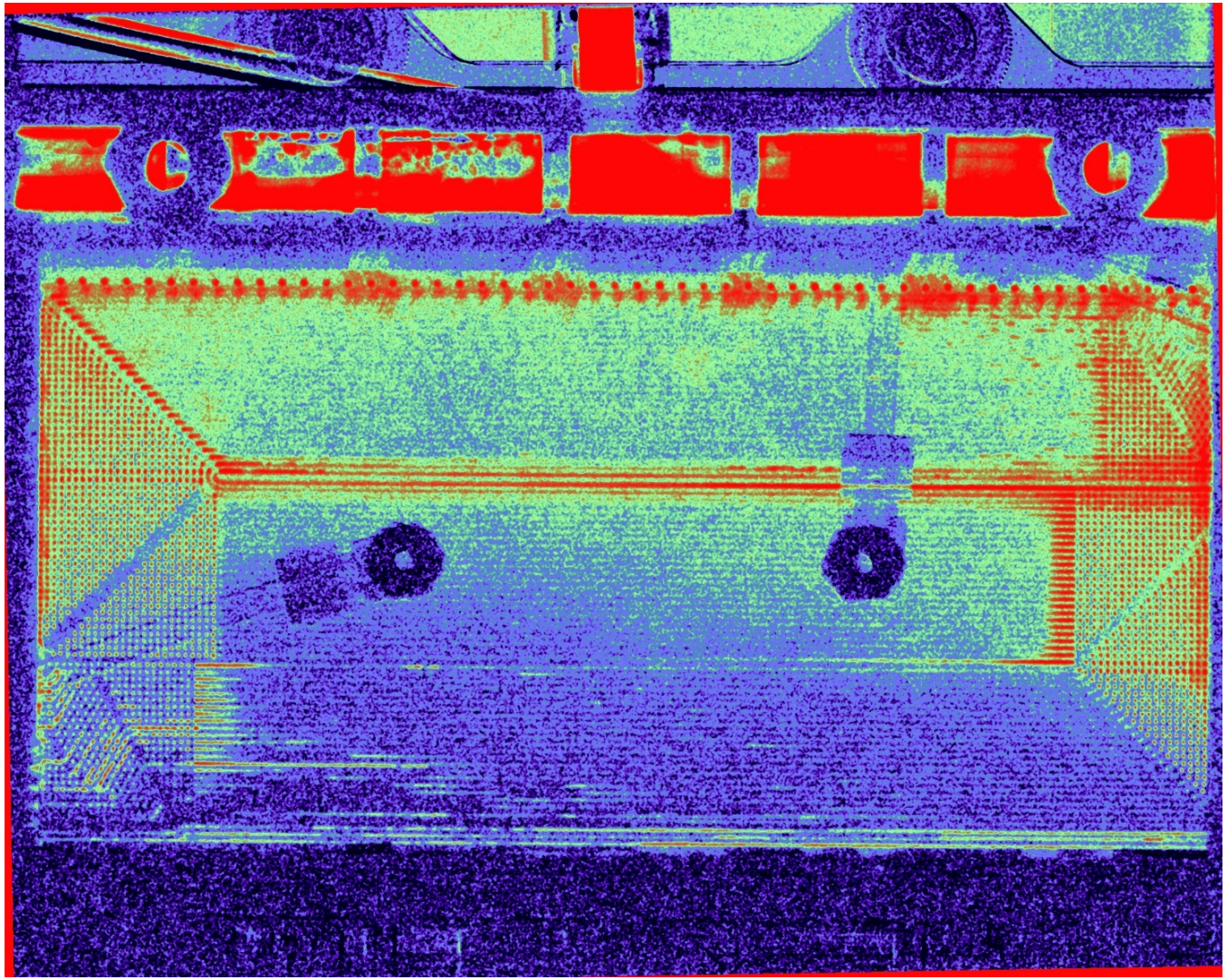
- 5 cell- 255 cm^2 active area per cell, the plate materials and Dimension/thickness labeled in picture.



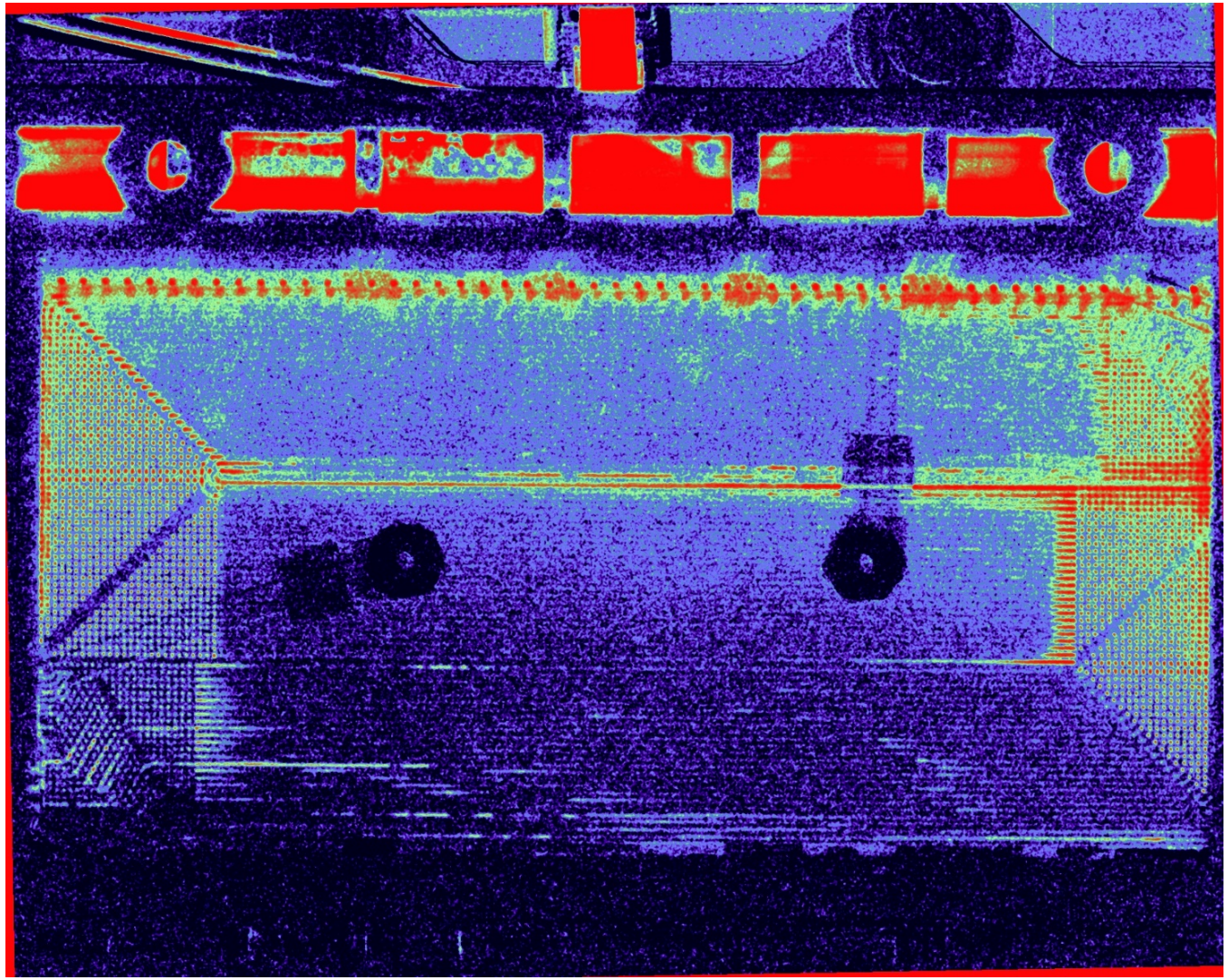
50A



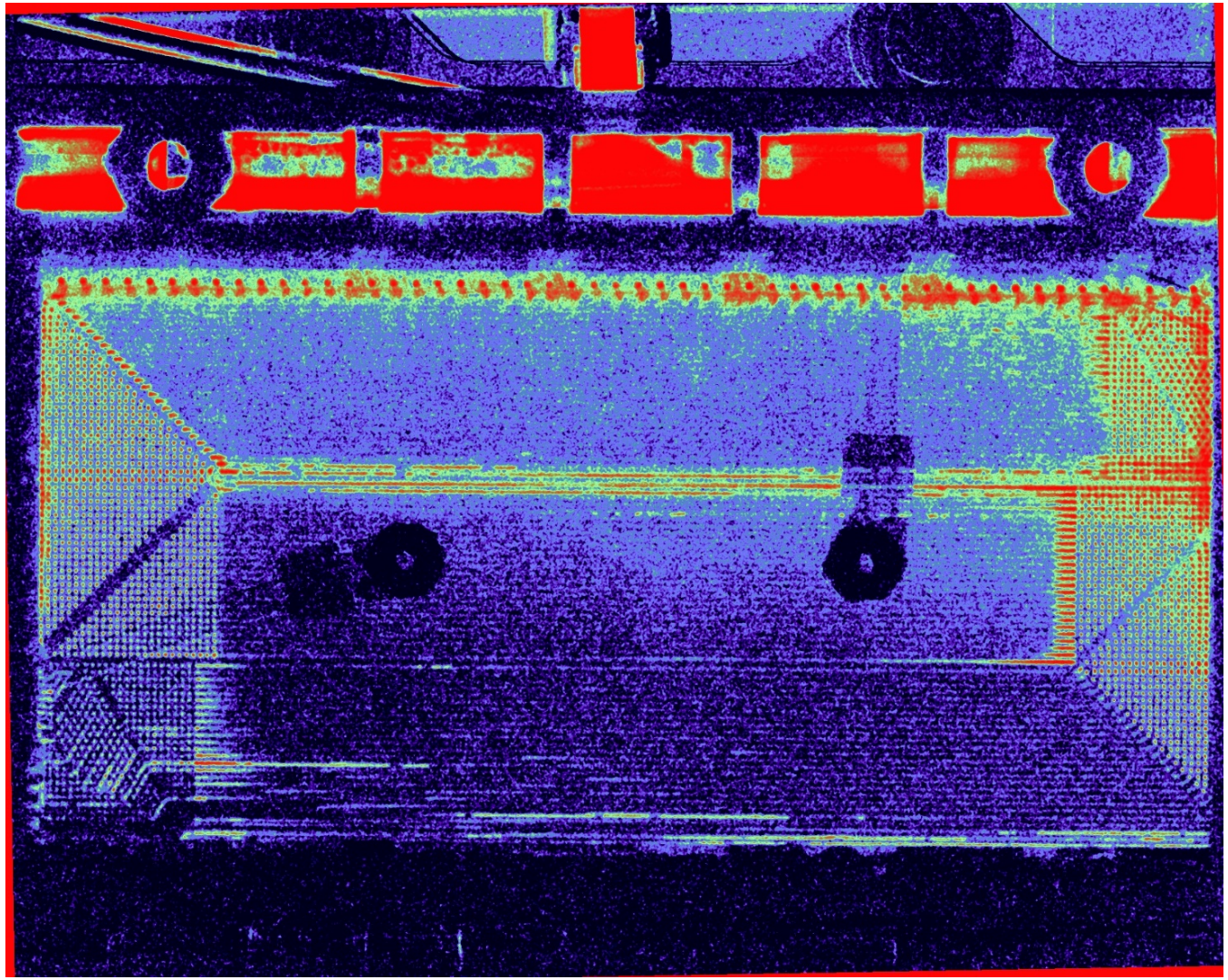
70A



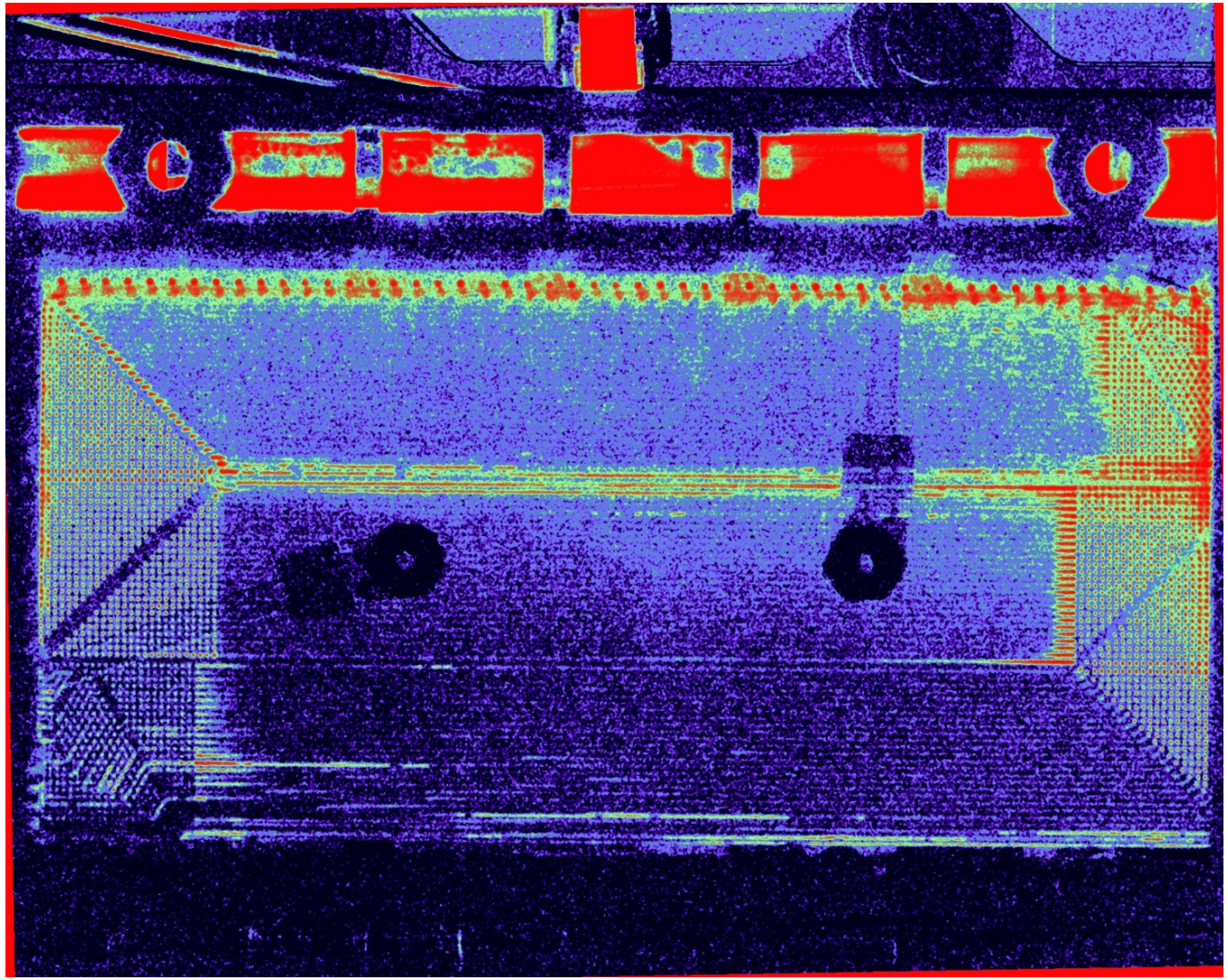
87.5A



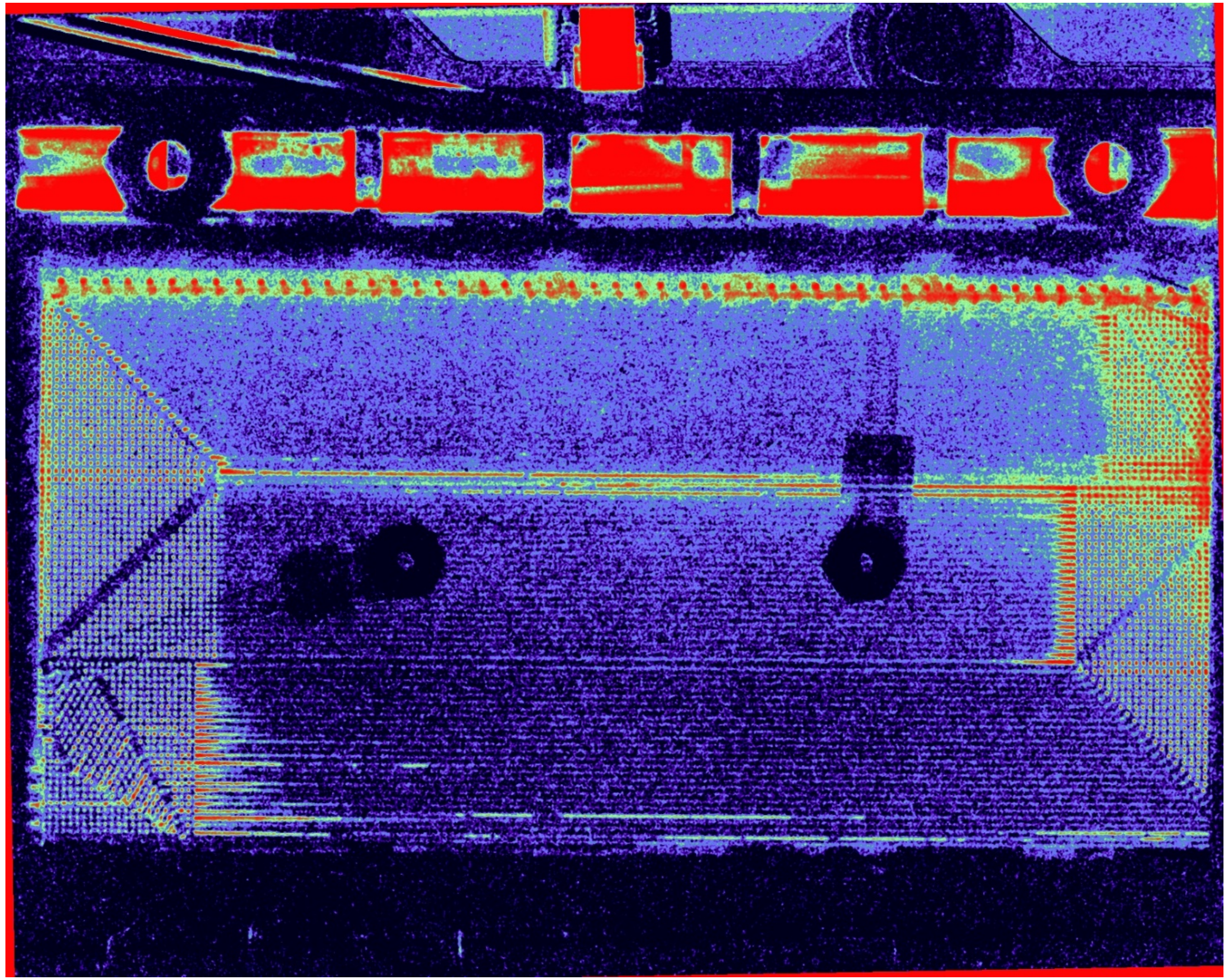
105A



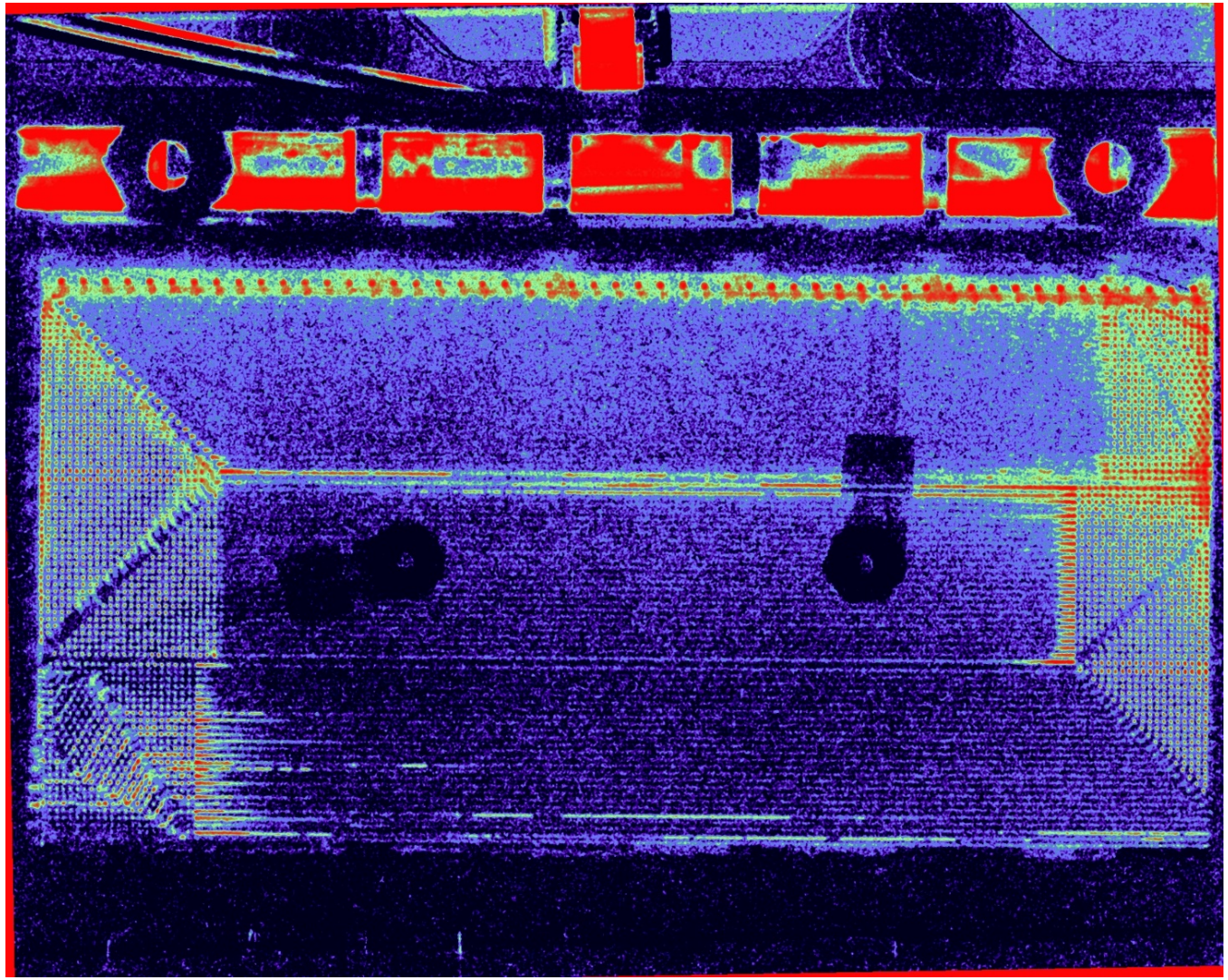
125A



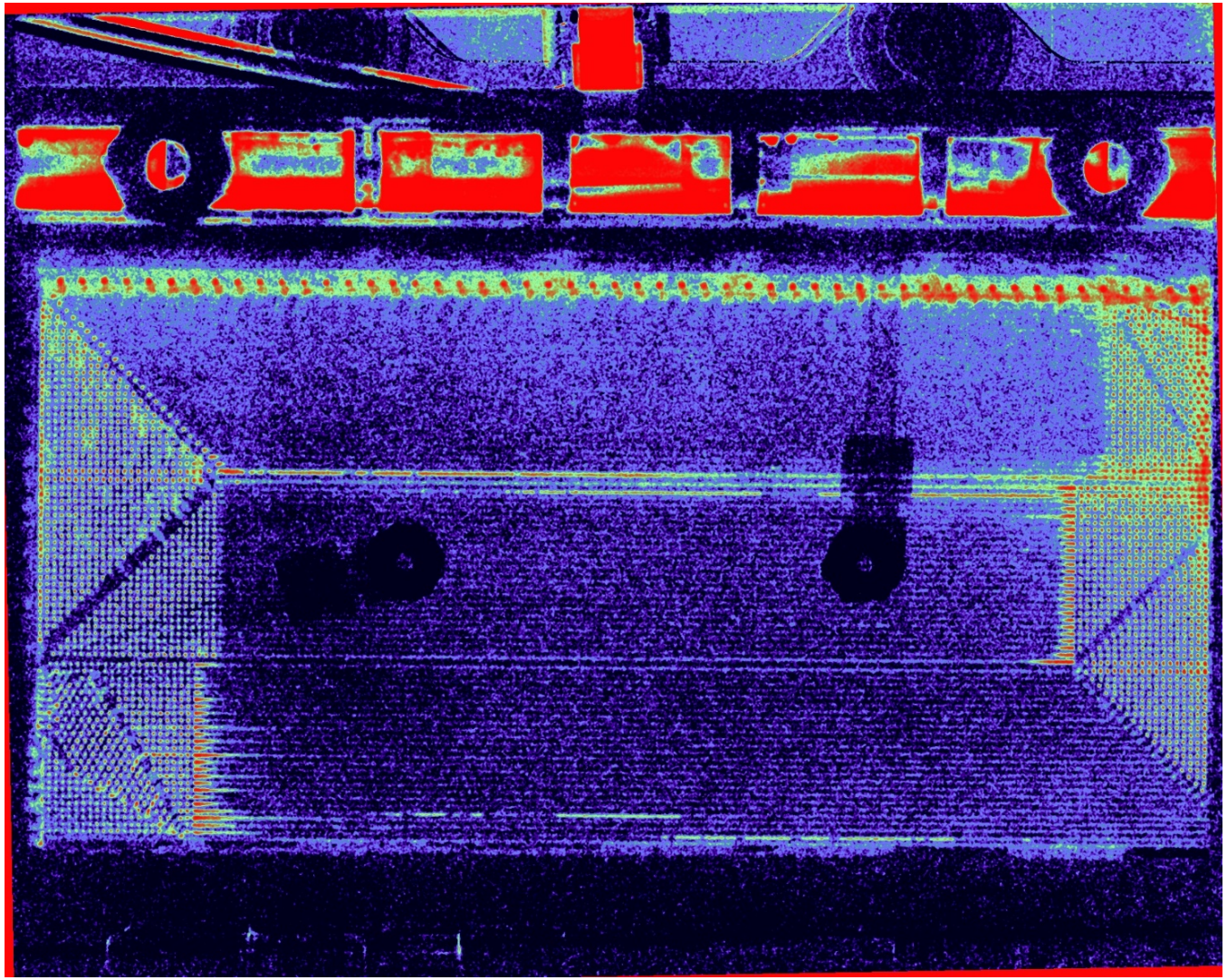
150A / 61C



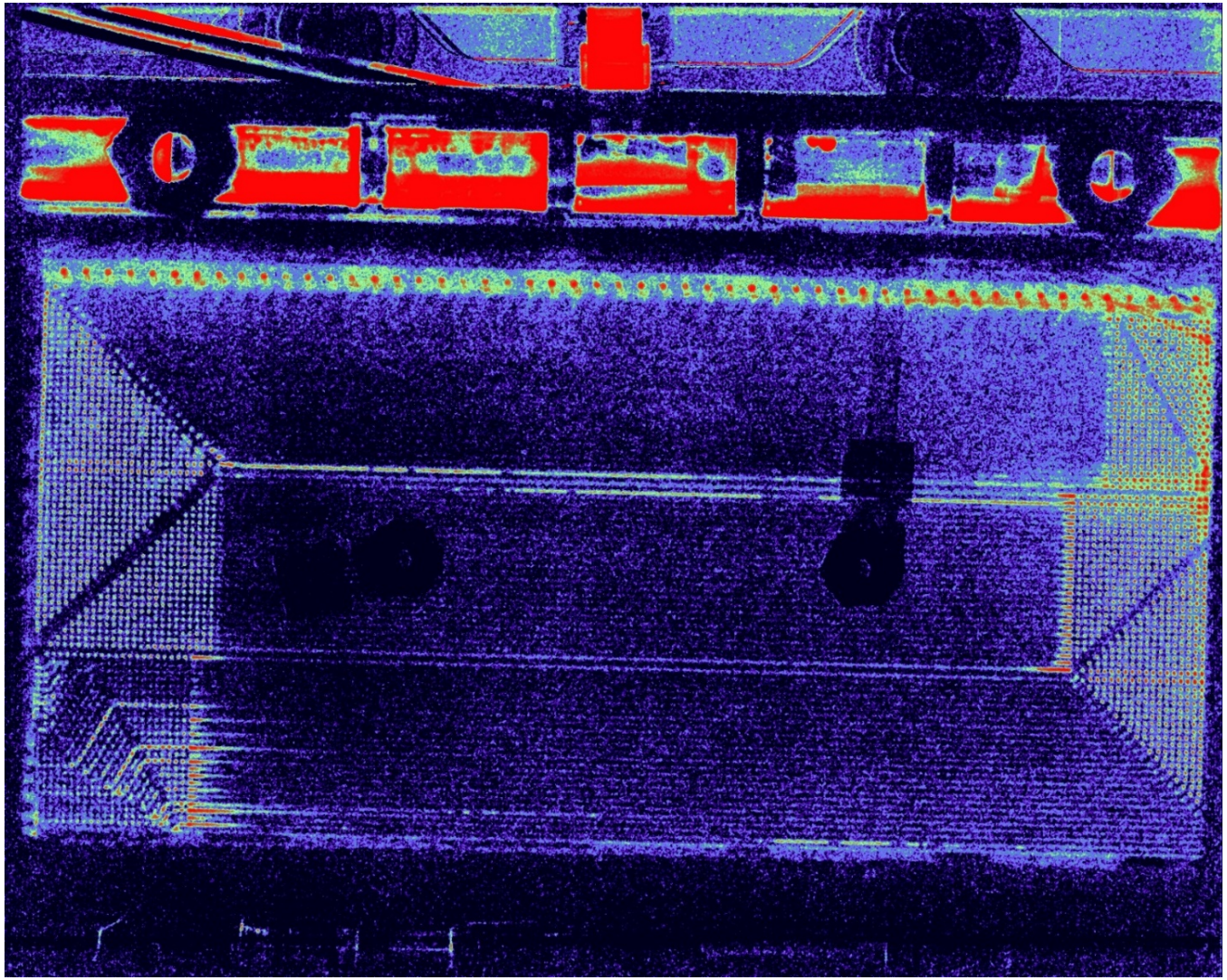
150A / 65C

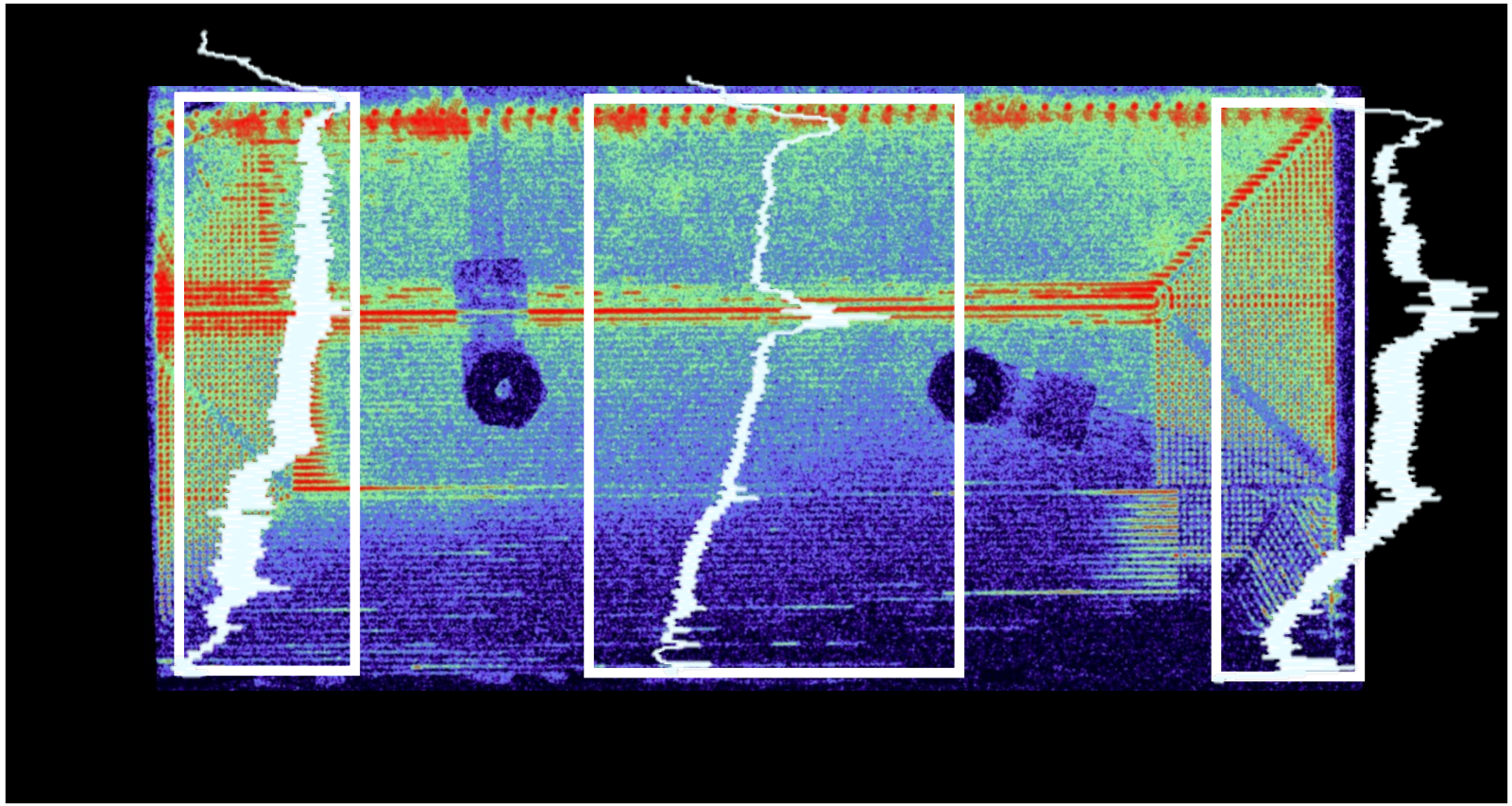


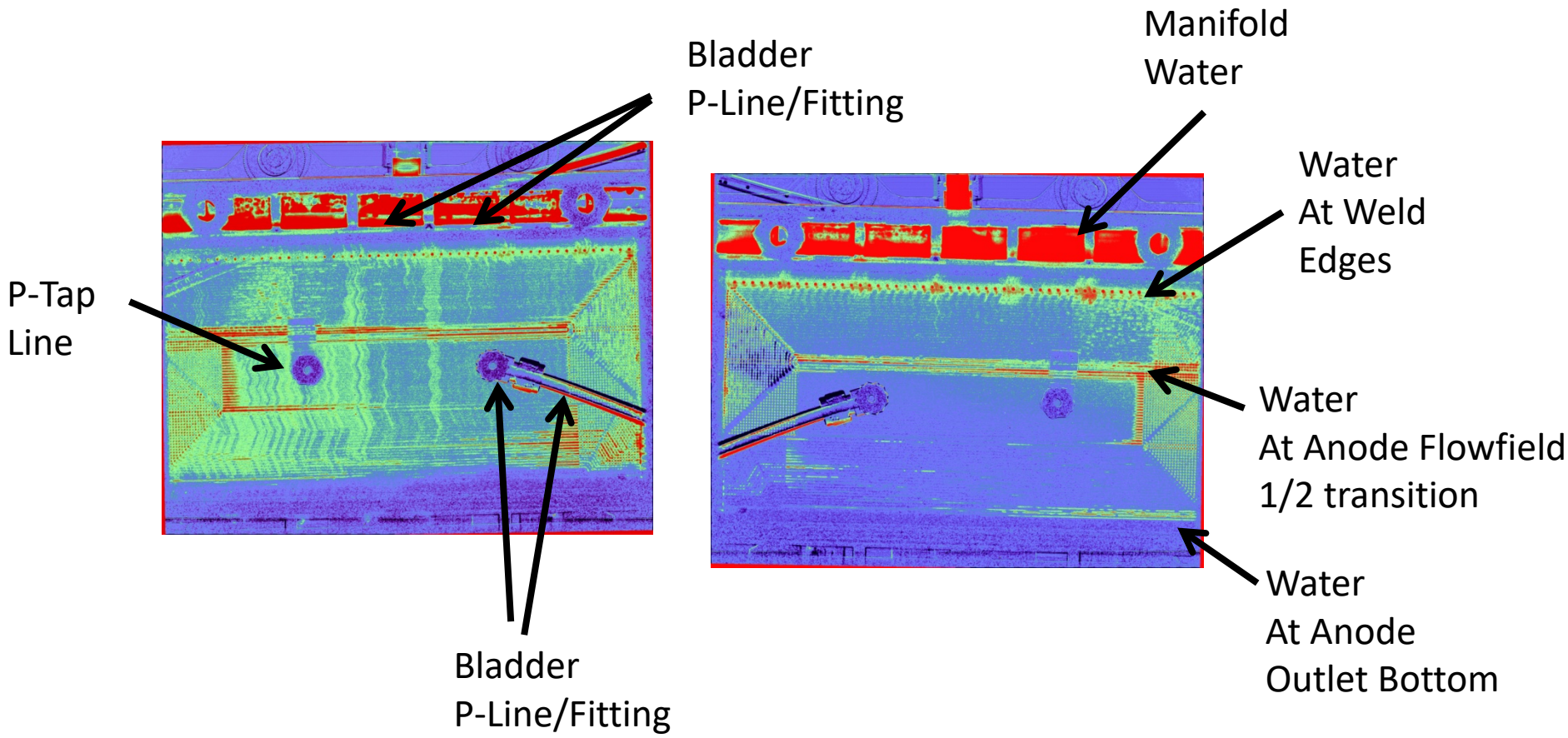
225A



312A






Bladder
P-Line/Fitting
Manifold
Water
Water
At Weld
Edges
P-Tap
Line
Water
At Anode Flowfield
1/2 transition
Water
At Anode
Outlet Bottom
Bladder
P-Line/Fitting